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POTENTIAL IMPACTS OF SEA LEVEL RISE ON THE BEACH AT OCEAN CITY, MARYLAND

by

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SUMMARY

Recent reports by the National Academy of Sciences and others have concluded that increasing atmospheric concentrations of carbon dioxide and other gases can be expected to cause a global warming that could raise sea level a few feet in the next century. Unfortunately, it is not yet possible to accurately predict future sea level. Estimates for the year 2025 range from five to twenty-one inches above current sea level, while estimates of the rise by 2100 range from two to eleven feet.

Several issues must be resolved for society to rationally address the possibility of a significant rise in sea level. Officials in coastal areas making decisions about near-term projects with long lifetimes must determine whether the risk of sea level rise justifies a shift to strategies that can more successfully accommodate a rise in sea level. The research community needs to decide whether to accelerate studies to more accurately project future sea level. These decisions require assessments of the adequacy of existing forecasts, prospects for improving the estimates, and the level of resources that can be saved if more definitive estimates become available.

These decisions also require an understanding of the consequences of sea level rise. To futher this understanding, EPA has initiated studies of the impacts of sea level rise on Charleston, South Carolina; Galveston, Texas; coastal wetlands; municipal drainage facilities; and salinity of surface and ground water.

This study examines the potential implications of sea level rise for efforts to control erosion of the beach at Ocean City, Maryland, a typical Atlantic Coast resort. Because current trends in sea level and other factors are already causing significant erosion at Ocean City and other ocean beach resorts, strategies for addressing coastal erosion constitute a class of near-term decisions that may depend on sea level rise. Because land and improvements are often worth well over one million dollars per acre in these areas, and erosion increases the likelihood of storm damage and federal disaster payments, the success of erosion control measures has great economic importance to the nation. We hope that this report will promote a reasoned consideration of the long-term consequences of sea level rise, and thereby enhance the eventual success of erosion control strategies at Ocean City and other coastal communities.

In this report, three independent teams of coastal process scientists estimate the erosion that will take place at Ocean City for three scenarios of future sea level rise: (1) current trends of 1 foot per century along the Atlantic coast; (2) the National Academy of Sciences estimate of a 2-1/3 foot global rise in the next century with an 11 inch rise by 2025; and (3) the EPA mid-high scenario of a global rise of 4-1/2 feet in the next century and 15 inches by 2025. The quantity of sand necessary to maintain the current shoreline is also estimated for each of the scenarios. Using these estimates and previous studies by the Corps of Engineers and others, the potential costs of erosion control are also examined.

CONCLUSIONS

1. Sea level rise could double the rate of erosion at Ocean City in the next forty years. If no additional erosion control measures are taken, the shore will erode 85-153 feet by 2025 assuming current sea level trends. An 11-inch global rise in sea level would increase expected erosion to between 180 and 238 feet, if no additional measures are taken; a 15-inch rise would increase expected erosion to between 216 and 273 feet.

2. The projected rise in sea level would increase the quantity of sand necessary to maintain the current shoreline for the next forty years from 5-10 million cubic yards if current trends continue, to 11-15 million cubic yards for the two scenarios of accelerated sea level rise.

3. Projected sea level rise would increase the priority of erosion control measures under current policies of the Corps of Engineers. Current policies place a greater emphasis on flood protection than recreational benefits provided by proposed projects. Because of the substantial erosion that could occur from a rise in sea level, the need for flood protection will be greater if sea level rises.

4. A significant rise in sea level would require a change in the technology used to control erosion at Ocean City. The current plan to construct groins was designed to curtail erosion caused by sand moving along the shore. However, groins do not prevent erosion caused by sea level rise. Placement of additional sand onto the beach would offset erosion caused by both sea level rise and alongshore transport.

5. The cost of controlling erosion caused by sea level rise does not threaten the economic viability of Ocean City in the next forty years. Even the most pessimistic estimate of future erosion control implies a cost of less than fifty cents for every visitor that comes to Ocean City each year. Protecting the shore at Ocean City will continue to be economically justified.

6. Understanding the likely impact of sea level rise on Ocean City in the next century will require identification of the most cost-effective and environmentally acceptable sources for up to fifty million cubic yards of sand to be placed on the beach.

7. Better estimates of future sea level rise would enable decision makers to more adequately determine the most prudent strategy for controlling erosion at Ocean City.

8. Although improved procedures for estimating erosion are desirable, current methods are sufficient to yield first-order estimates for use in long-term planning.

ACKNOWLEDGMENTS

We wish to express our appreciation for the numerous people who provided helpful contributions and encouraged us to publish this report. Torrey Brown and Sarah Taylor of the Maryland Department of Natural Resources initially requested that EPA use the Ocean City situation as a case study of sea level rise impacts. Sandy Coyman of Ocean City's Department of Planning and Community Development provided numerous editorial contributions to make the report more readable. Ed Fulford and Suzette May of the Army Corps of Engineers provided several important insights concerning erosion processses along the Maryland coast.

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Dennis Tirpak and John S. Hoffman of EPA's Office of Policy Analysis made important organizational contributions to Chapter 1. William Hoffman and Marria O'Malley of EPA's Region III reviewed the report from the perspective of wetland and marine policy. Susan MacMillan of ICF Incorporated and Joan O'Callaghan of EPA provided detailed editorial contributions. Finally, Margo Brown prepared the manuscript.

Without the contributions of these and other people who encouraged us along the way, this report would not have been possible.

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CHAPTER I

SEA LEVEL RISE AND THE MARYLAND COAST

by
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INTRODUCTION

In the last few decades, Americans have increasingly used the resources offered by our coastal areas. The popularity of beaches now accounts for a multibillion dollar industry. Recreational hunting and fishing, while less significant nationwide, are major attractions in coastal wetlands and estuaries, such as Louisiana's marshes and swamps, Chesapeake Bay, and Narragansett Bay.[1] Recreational boating has also become more widespread in coastal areas.[2]

To accommodate increasing numbers of visitors, modern high-rise hotels and condominiums, houses, and marinas have replaced the small cottages and vacant land that once characterized ocean beach resorts and barrier islands. High land values have sometimes encouraged people to create land by filling marshes and shallow bays. Many mainland areas within a short commute to the beach are also being developed extensively.

Increasing development has entailed certain economic and environmental risks. Buildings in many coastal areas are vulnerable to severe storms which generally occur every thirty to fifty years (Kunreuther 1978). In many areas, the beaches are eroding, which gradually removes an important recreational asset and increases the vulnerability of shorefront property to storms. The filling of coastal marshes has sometimes destroyed fish and wildlife habitats and impaired water quality in coastal areas (Office of Technology Assessment 1984). Bulkheads that eliminate natural bay beaches can threaten the food supply of shore birds.

Congress has enacted several policies to address these risks. In 1968 it found that "many factors have made it uneconomic for the private insurance industry alone to make flood insurance available."[3] As a result, it enacted the National Flood Insurance Act which requires property owners with federally insured mortgages in coastal hazard areas to obtain flood insurance, and requires participating communities to take measures to ensure that newly constructed buildings will not be destroyed by a major storm. In 1972 Congress declared that it is national policy to "preserve, protect, develop, and where possible to restore or enhance, the resources of the nation's coastal zones for this and succeeding generations"[4] and passed the Coastal Zone Management Act, which encourages states to develop coastal policies to ensure that new development is safe and provides for the conservation of wetlands and other natural environments. The Coastal Barrier Resources Act forbids federal subsidies to designated undeveloped barrier islands. Section 404 of the Clean Water Act requires anyone wishing to build on a coastal marsh to obtain a permit from the Army Corps of Engineers with approval by the Environmental Protection Agency. Finally, the National Environmental Policy Act requires an environmental impact statement informing the public of potential environmental risks for any major federal action, including a permit under Section 404.

These programs are generally administered by state and local governments. Over seventeen thousand communities participate in the National Flood Insurance Program, which requires them to enact zoning and building codes to prevent excessively hazardous construction. States develop coastal zone management plans subject to approval by the federal government. Provided that the necessary assessments and permits are filed, the decision whether to fill a marsh is primarily a local land use decision. Many states and localities have gone beyond federal requirements and effectively prohibited the construction of bulkheads or filling of coastal marshes.[5] These and other federal, state, and local policies have reduced the economic and environmental risks of developing coastal areas.

Recent scientific findings, however, suggest that current policies may be overlooking an environmental impact that could exacerbate the other risks: a rise in the level of the oceans. Increasing atmospheric concentrations of carbon dioxide and other gases are expected to warm our planet a few degrees centigrade in the next century by a mechanism known as the "greenhouse effect." Such a global warming would probably cause sea level to rise more rapidly than it is currently. Although estimates of the rise expected in the next one hundred years range from 38 to 211 centimeters (15 inches to 8 feet), a precise forecast will not be possible in the foreseeable future.

Even a thirty-centimeter (one-foot) rise in sea level would have important environmental impacts and would change the consequences of decisions made today. Along the open coast, beaches could erode 20 to 80 meters (60 to 250 feet), and buildings would be more vulnerable to storms (Bruun 1962). Along the shores of coastal estuaries, existing marshes would drown and homeowners in some areas would have to build levees and bulkheads to prevent new marshes from taking over their properties (Kana, Baca, and Williams 1985).

With a rise of one meter, most coastal communities would have to choose between several undesirable alternatives: investing substantial resources to maintain beaches and wetlands in their current locations; building seawalls and bulkheads to protect property while allowing beaches and marshes to erode away; or allowing beaches and marshes to encroach inland onto previously developed land. Fortunately, many of the potential costs can be avoided or reduced if timely measures are taken in anticipation of sea level rise (Barth and Titus 1984).

This report examines the erosion that sea level rise could cause the resort community of Ocean City, Maryland, over the next ninety years. Like many resorts, Ocean City has an erosion problem. Although city and state agencies are undertaking measures to reduce erosion, their strategies do not yet consider the impacts of rising sea level. We hope that this report will help promote a reasoned consideration of the long-term consequences of sea level rise, and thereby enhance the eventual success of erosion control strategies at Ocean City.* We also encourage other coastal communities with erosion problems to consider the implications of a rising sea.

In the following chapters, three coastal research teams describe their independent assessments of beach erosion from sea level rise and other

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* This report does not consider options for reducing the rise in sea level due to the greenhouse effect. See Lovins et al. (1981) and Seidel and Keyes (1983) for discussions of this issue.

factors. In Chapter 2, Leatherman presents "Geomorphic Effects of Accelerated Sea Level Rise on Ocean City, Maryland," with an appendix by Bresee. In Chapter 3, Everts presents "Effect of Sea Level Rise and Net Sand Volume Changes on Shoreline Position at Ocean City, Maryland." Finally, in Chapter 4, Kriebel and Dean present "Estimates of Erosion and Mitigation Requirements under Various Scenarios of Sea Level Rise and Storm Frequency for Ocean City, Maryland."

In this introductory chapter, written for the general reader, we summarize the results of those studies and other relevant information. We describe the basis for expecting a significant rise in sea level in the future; provide an overview of the possible impacts on Maryland and other coastal areas; summarize the three studies presented in Chapters 2 through 4; and briefly discuss the implications of these studies and additional steps that could help Ocean City and similar communities prepare for the consequences of future sea level rise. Because this study focuses primarily on erosion and beach nourishment, a more thorough assessment of the long-term economic and policy implications should be undertaken using the technical data this report provides.

THE BASIS FOR EXPECTING A RISE IN SEA LEVEL

Past Trends in Sea Level

Throughout geologic history, sea level has risen and fallen by over three hundred meters (one thousand feet) due to changes in (1) the shape and size of ocean basins, (2) the amount of water in the oceans, and (3) the average density of seawater. The emergence and submergence of land has also changed sea level relative to particular land masses. The first three factors influence "global sea level"; the latter affects "relative sea level."

In the last 100 million years, changes in the size and shape of ocean basins have caused the greatest changes in global sea level (Hays and Pitman 1973). However, in the last several thousand years, these processes have usually been relatively slow and are not likely to accelerate in the near future.[6]

Sea level has risen and fallen with past changes in world climate. During the ice ages, the average global temperature has been 5°C colder than today (Hansen et al. 1984). With glaciers covering much of the northern hemisphere, there has been less water in the oceans and the sea level has been one hundred to one hundred fifty meters (three hundred to five hundred feet) lower than today (Donn, Farrand, and Ewing 1962). During previous interglacial (warm) periods, on the other hand, global temperatures have been 1-2°C warmer than today and sea level has been about six meters (twenty feet) higher (Hollin 1972).

Although the glaciers that covered much of the northern hemisphere during the last ice age have melted, polar glaciers in Greenland and Antarctica contain enough water to raise sea level more than seventy meters (over two hundred feet) (Untersteiner 1975). A complete melting of these glaciers has not occurred in the last two million years, and would take tens of thousands of years even if the earth warmed substantially. However, unlike the other glaciers which rest on land, the west antarctic ice sheet is marine-based and more vulnerable to temperature increases. Warmer ocean water would be more effective than warmer air at melting glaciers, causing West Antarctica to melt. Mercer (1970) suggests that the west antarctic ice sheet completely disappeared during the last interglacial period, raising sea level five to seven meters (about twenty feet) above its present level.

Over relatively short periods of time, climate can influence sea level by heating and thereby expanding (or cooling and contracting) sea water. In the last century, tidal gauges have been available to measure relative sea level in particular locations. Along the Atlantic Coast, sea level has risen about 30 centimeters (one foot) in the last century (Hicks, Debaugh, and Hickman 1983). Studies combining all the measurements have concluded that average worldwide sea level has risen ten to fifteen centimeters (four to six inches) in the last one hundred years (Barnett 1983; Gornitz, Lebedeff, and Hansen 1982). At least part of this rise can be explained by the thermal expansion of the upper layers of the oceans resulting from the observed warming of 0.4°C in the last century (Gornitz, Lebedeff, and Hansen 1982). Meltwater from mountain glaciers has also contributed to sea level rise (Meier 1984). Figure 1 shows that global temperature and sea level have been rising in the last century. Nevertheless, questions remain over the magnitude and causes of sea level rise in the last century.

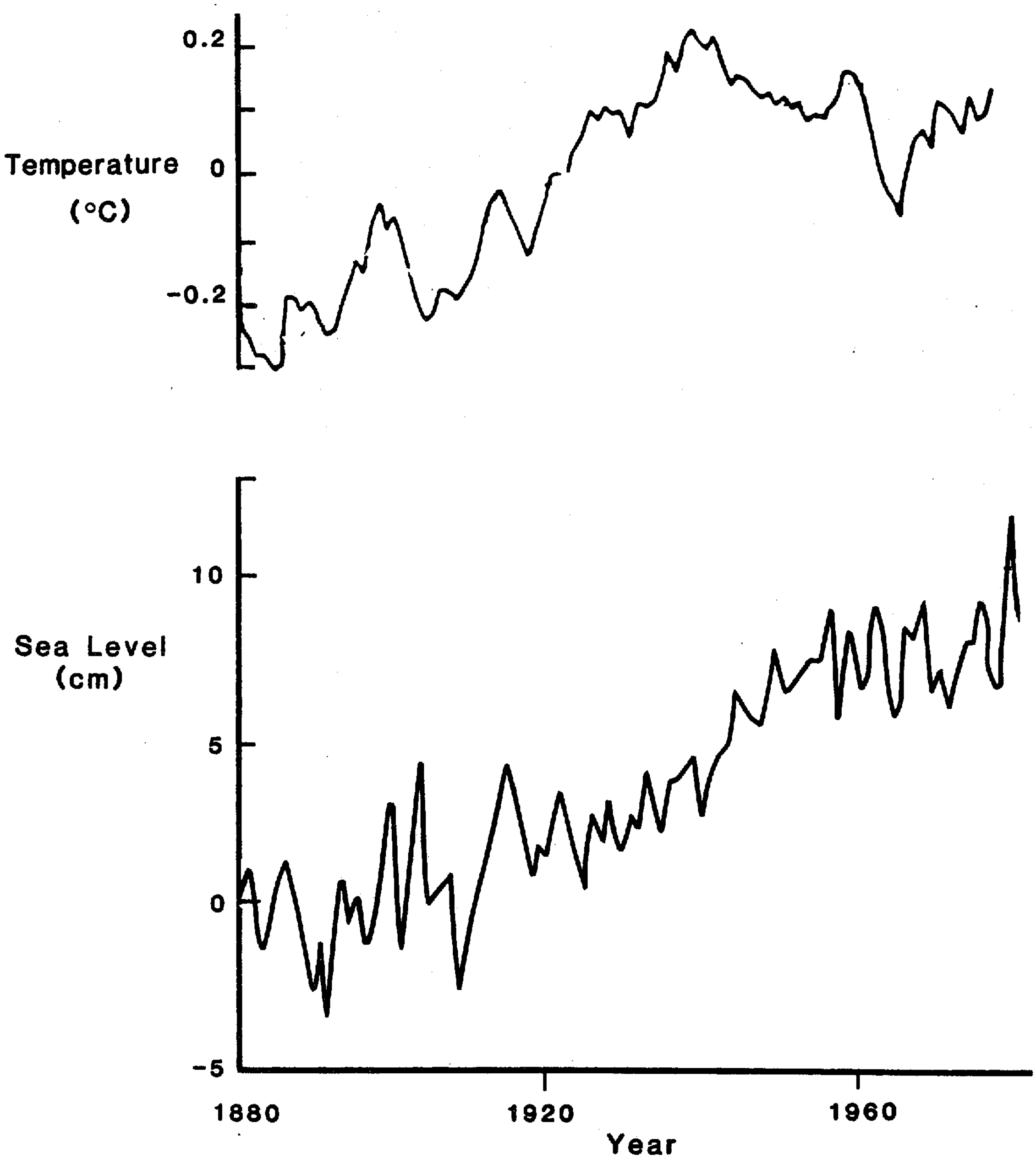
The Greenhouse Effect

Concern about a possible acceleration in the rate of sea level rise arises from measurements that concentrations of carbon dioxide (CO_2), methane, chlorofluorocarbons, and other gases released by human activities are increasing. Because these gases absorb infrared radiation (heat), scientists generally expect the earth to warm substantially. Although some people have suggested that unknown or unpredictable factors could offset this warming, the National Academy of Sciences (NAS) has twice reviewed all the evidence and concluded that the warming will take place. In 1979, the Academy concluded: "We have tried but have been unable to find any overlooked physical effect that could reduce the currently estimated global warming to negligible proportions" (Charney 1979). In 1982, NAS confirmed the 1979 assessment (Smagorinsky 1982).

A planet's temperature is determined primarily by the amount of sunlight it receives, the amount of sunlight it reflects, and the extent to which its atmosphere retains heat. When sunlight strikes the earth, it warms the surface, which then reradiates the heat as infrared radiation. However, water vapor, CO_2, and other gases in the atmosphere absorb some of the energy rather than allowing it to pass undeterred through the atmosphere to space. Because the atmosphere traps heat and warms the earth in a manner somewhat analogous to the glass panels of a greenhouse, this phenomenon is generally known as the "greenhouse effect." Without the greenhouse effect of the gases that occur in the atmosphere naturally, the earth would be approximately 33°C (60°F) colder than it is currently (Hansen et al. 1984). Thus, the greenhouse effect <u>per</u>

FIGURE 1

GLOBAL TEMPERATURES AND SEA LEVEL HAVE RISEN IN THE LAST CENTURY



Sources: Temperature curve from: J.E. Hansen et al., "Climate Impact of Increasing Atmospheric Carbon Dioxide," Science, 1981, p. 957-966. Sea level curve adapted from: V. Gornitz, S. Lebedeff, and J. Hansen, "Global Sea Level Trend in the Past Century," Science, 1982, p. 1611-1614.

se is not something that will happen; it is a natural characteristic of the atmosphere.

In recent decades, the concentrations of these "greenhouse gases" have been increasing. Since the industrial revolution, the combustion of fossil fuels, deforestation, and cement manufacture have released enough CO_2 into the atmosphere to raise the atmospheric concentration of carbon dioxide by 20 percent (Keeling, Bacastow, and Whorf 1982). As Figure 2 shows, the concentration has increased 8 percent since 1958. Recently, the concentrations of methane, nitrous oxide chlorofluorocarbons and some other trace gases that also absorb infrared radiation have also been increasing (Lacis et al. 1981; Ramanathan et al. 1985).

Although there is no doubt that the concentration of greenhouse gases is increasing, the future rate of that increase is uncertain. A recent report by the National Academy of Sciences (NAS) examined numerous uncertainties regarding future energy use patterns, economic growth, and the extent to which CO_2 emissions remain in the atmosphere (Nordhaus and Yohe 1983). The Academy estimated a 98 percent probability that CO_2 concentrations will be at least 450 parts per million (1.5 times the preindustrial level) by 2050 and a 55 percent chance that the concentration will be 550 parts per million. The Academy estimated that the probability of a doubling of CO_2 concentrations by 2100 is 75 percent.

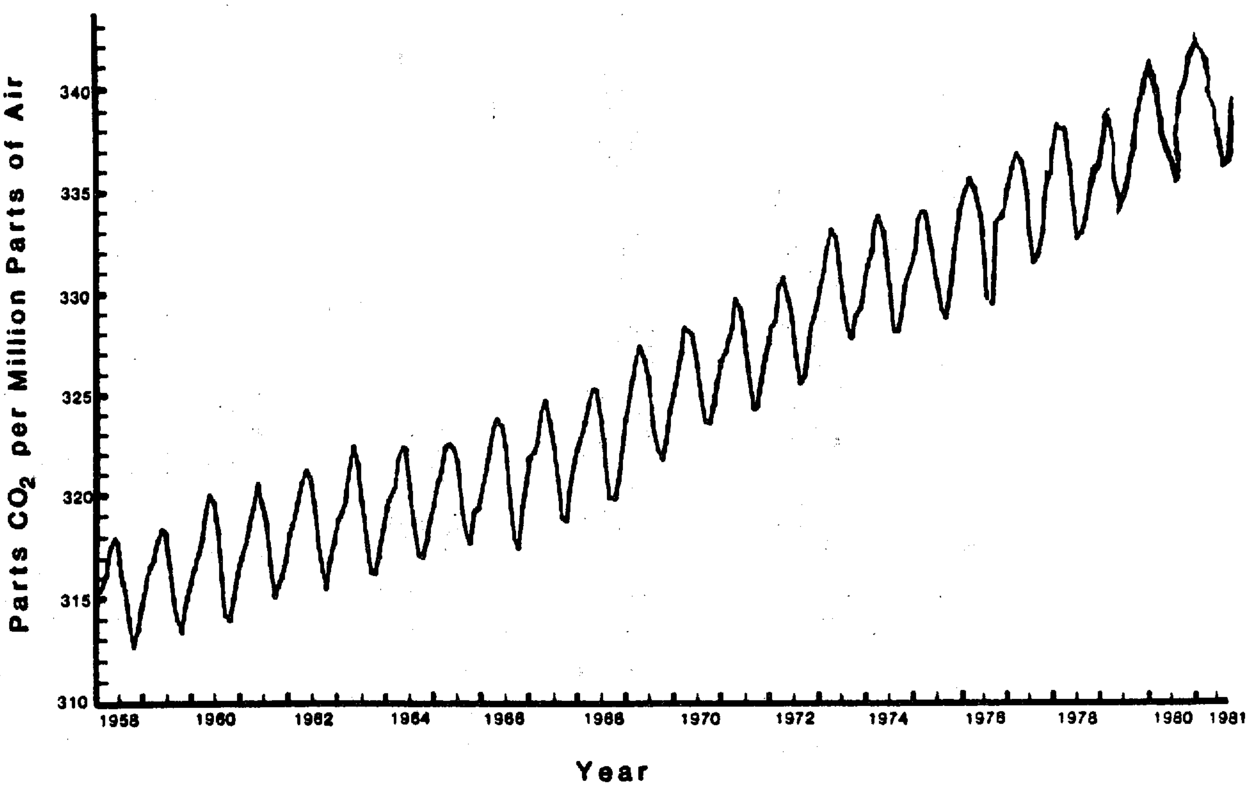
If the impact of the trace gases continues to be equal to the impact of CO_2, NAS analysis implies that the effective doubling of all greenhouse gases has a 98 percent chance of occurring by 2050.[7] However, uncertainties regarding the emissions of trace gases are greater than those for CO_2. Although the sources of chlorofluorocarbon emissions are well documented, regulatory uncertainties related to their possible impact on stratospheric ozone depletion make their growth rate -- currently about 5 percent -- impossible to forecast. The current sources of methane, nitrous oxide, and other trace gases have not yet been fully catalogued.

Considerable uncertainty also exists regarding the impact of a doubling of greenhouse gases. Physicists and climatologists generally accept the estimate by Hansen et al. (1984) that a doubling would directly raise the earth's average temperature 1.2°C if nothing else changed. However, if the earth warmed 1.2°C, many other aspects of climate would be likely to change, probably amplifying the direct effect of the greenhouse gases. These indirect impacts are known as "climatic feedbacks."

Figure 3 shows estimates by Hansen et al. (1984) of the most important known feedbacks. A warmer atmosphere would retain more water vapor, which is also a greenhouse gas, warming the earth more. Snow and floating ice would melt, decreasing the amount of sunlight reflected to space, causing additional warming. Although the estimates of other researchers differ slightly from those of Hansen et al., climatologists agree that these two feedbacks would amplify the global warming from the greenhouse effect. However, the impact of clouds is far less certain. Although recent investigations have estimated that changes in cloud height and cloud cover would add to the warming, the possibility that changes in cloud cover would offset part of the warming

FIGURE 2

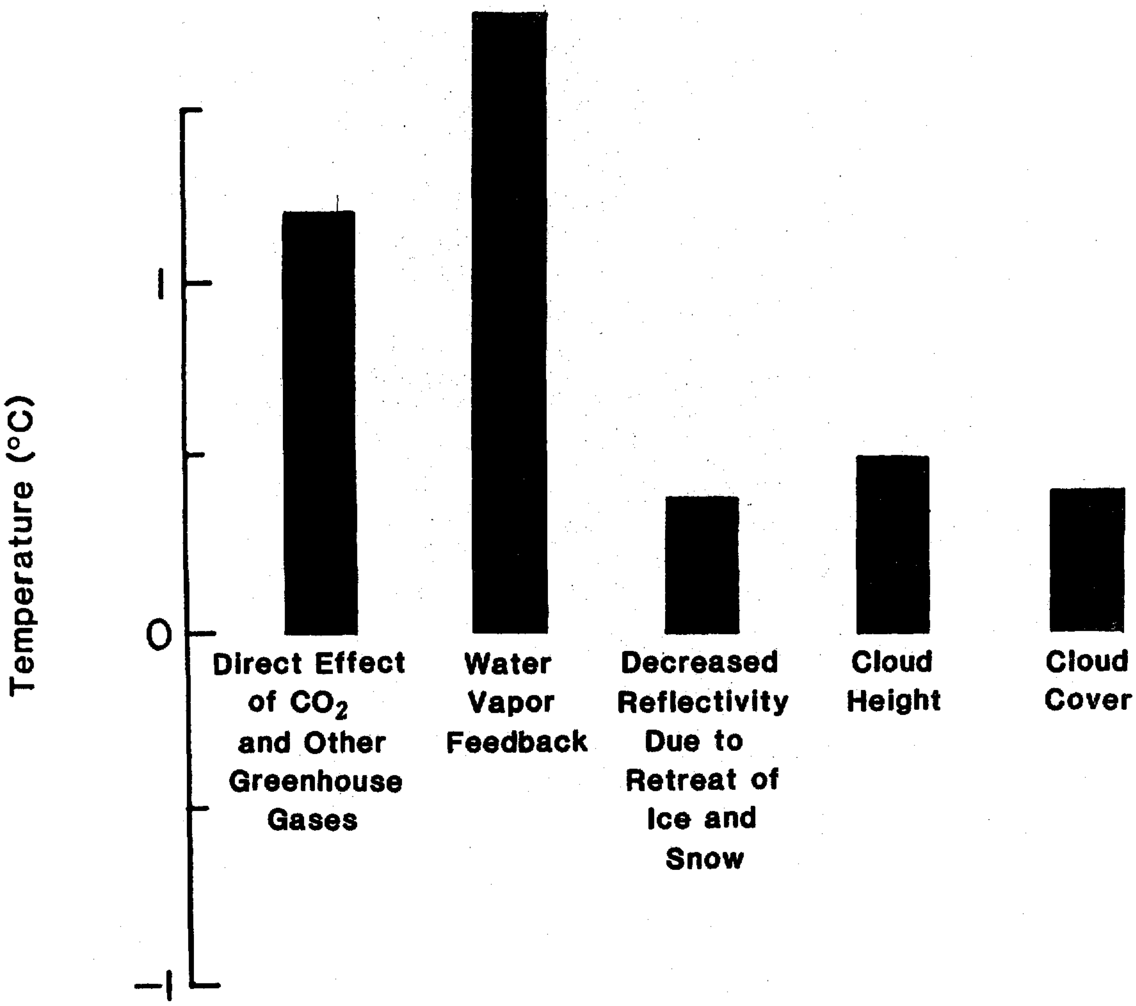
MEASUREMENTS OF ATMOSPHERIC CARBON-DIOXIDE ABUNDANCE OVER TIME: 1958 to 1981



Sources: Mauna Loa Observatory, Hawaii, NOAA, U.S. Department of Commerce.

FIGURE 3

ESTIMATED GLOBAL WARMING DUE TO A DOUBLING OF GREENHOUSE GASES: DIRECT EFFECTS AND CLIMATIC FEEDBACKS



Although Hansen et al. estimate a positive feedback from the clouds, a negative feedback cannot be ruled out.

Sources: Adapted from: J.E. Hansen, et al., "Climate Sensitivity to Increasing Greenhouse Gases," in <u>Greenhouse Effect and Sea Level Rise: A Challenge for This Generation</u>, edited by M.C. Barth and J.G. Titus. New York: Van Nostrand Reinhold, 1984, p. 62.

cannot be ruled out. After evaluating the evidence, two panels of the National Academy of Sciences concluded that the eventual warming from a doubling of greenhouse gases would be between 1.5° and 4.5°C (3°-8°F).

A global warming of a few degrees could be expected to raise sea level in the future, as it has in the past. The best understood mechanism is the warming and resulting expansion of sea water, which could raise sea level one-half meter in the next century (Hoffman, Keyes, and Titus 1983). Mountain glaciers could melt and release enough water to raise sea level twelve centimeters (five inches) (Revelle 1983). Revelle estimates that a 3°C warming could cause Greenland's glaciers to melt enough water to raise the sea another twelve centimeters in the next century. Antarctica could contribute to sea level rise either by meltwater running off or by glaciers sliding into the oceans.

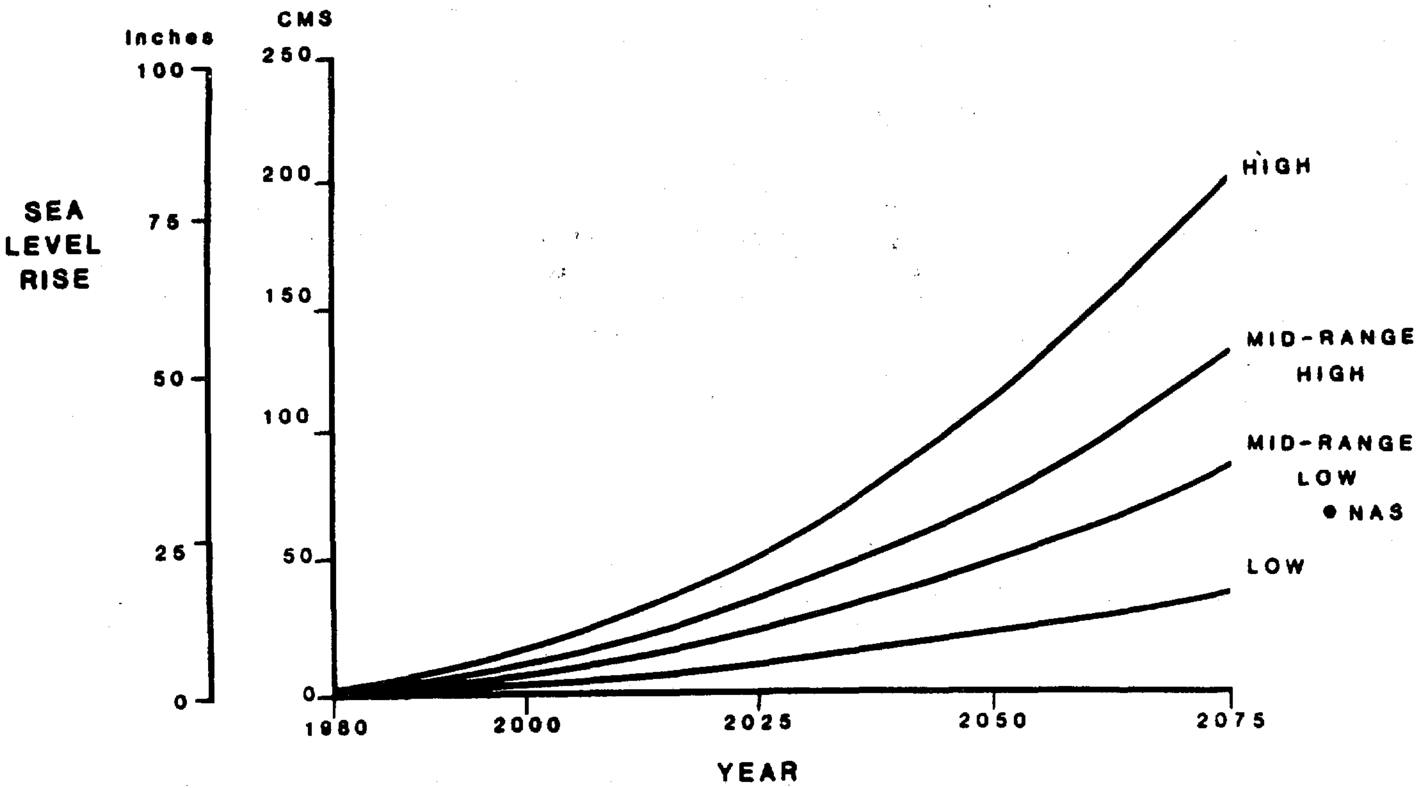
Recent analysis by the Polar Research Board of the National Academy of Sciences indicates that glaciers in Greenland and East Antarctica, as well as those in West Antarctica, could eventually release enough ice into the oceans to raise sea level two or three centimeters (about one inch) per year.[8] However, current thinking holds that such a rapid rise is at least one hundred years away. Moreover, a complete disintegration of the West Antarctic Ice Sheet would take several centuries (Bentley 1983; Hughes 1983). It is possible that snowfall accumulation could partially offset the rise in sea level.[9]

In 1983, two independent reports estimated future sea level rise. In the National Academy of Sciences report Changing Climate, Revelle estimated that the combined impacts of thermal expansion, Greenland and mountain glaciers could raise sea level seventy centimeters (two and one-third feet) in the next century (Revelle 1983). Although he also stated that Antarctica could contribute two meters per century to sea level starting around 2050, Revelle did not add this contribution to his estimate.

In a report by the Environmental Protection Agency entitled Projecting Future Sea Level Rise, Hoffman, Keyes, and Titus (1983) stated that the uncertainties regarding the factors that could influence sea level are so numerous that a single estimate of future sea level rise is not practical. Instead, they consulted the literature to specify high, medium, and low estimates for all the major uncertainties, including fossil fuel use; the absorption of carbon dioxide through natural processes; future emissions of trace gases; the global warming that would result from a doubling of greenhouse gases (the NAS estimate of 1.5°-4.5°C); the diffusion of heat into the oceans; and the impact of ice and snow. They estimated that if all of the low assumptions prove to be correct, the sea will rise 13 cm (5 in) by 2025 and 38 cm (15 in) by 2075 over the 1980 level. If all of the high assumptions are correct, the sea will rise 55 cm (2 ft) by 2025 and 211 cm (7 ft) by 2075. However, because it is very unlikely that either all the high or all the low assumptions will prove to be correct, the authors concluded that the rise in sea level is likely to be between two mid-range scenarios of 26 to 39 cm (11 to 15 in) by 2025 and 91 to 136 cm (3 to 4-1/2 ft) by 2075. Figure 4 and Table 1 illustrate the EPA and NAS estimates. Although neither of these studies examined options to limit the rise in sea level by curtailing

FIGURE 4

GLOBAL SEA LEVEL RISE SCENARIOS:
LOW, MID-RANGE LOW, MID-RANGE HIGH, AND HIGH



Sources: J. Hoffman, D. Keyes, and J. Titus, Projecting Future Sea Level Rise, Washington, D.C.: Government Printing Office, 1983; Changing Climate, Washington, D.C.: NAS Press, 1983 (does not include Antarctica).

TABLE 1

SCENARIOS OF WORLDWIDE SEA LEVEL RISE
(centimeters)

	2000	2025	2050	2075	2080	2100
Current Trends	2.0-3.0	4.5-6.8	7.0-10.5	9.5-14.3	10-15	12.0-18.0
EPA Scenarios						
High	17.1	54.9	116.7	211.5	-	345.0
Mid-range high	13.2	39.3	78.9	136.8	-	216.6
Mid-range low	8.8	26.2	52.6	91.2	-	144.4
Low	4.8	13.0	23.0	38.0	-	56.2
NAS Estimate (excluding Antarctic Contribution)	-	-	-	-	70.0	-

emissions, Seidel and Keyes (1983) estimated that even a ban on coal, shale oil, and synfuels would only delay the rise in sea level expected through 2050 by twelve years.[10]

The East Coast of the United States is slowly sinking (Hoffman, Keyes, and Titus 1983). Thus relative sea level rise at Ocean City, Maryland, will be fifteen to twenty centimeters (six to eight inches) greater than global sea level rise per century. Table 2 displays the projected rise at Ocean City for the EPA mid-range scenarios and current trends.

TABLE 2

RELATIVE SEA LEVEL RISE SCENARIOS FOR OCEAN CITY, MARYLAND (absolute rise over 1980 level in centimeters (feet))

Year	Current Trend	Mid-Range Low Rise	Mid-Range High Rise
2000	7 (0.24)	12.4 (0.40)	16.8 (0.55)
2025	16 (0.53)	34.3 (1.13)	47.4 (1.55)
2050	25 (0.83)	65.2 (2.14)	91.5 (3.00)
2075	34 (1.13)	108.3 (3.55)	153.9 (5.05)

Sources: J. Hoffman, D. Keyes, and J. Titus, Projecting Future Sea Level Rise, Washington, D.C.: Government Printing Office, 1983.
R. Revelle, "Probable Future Changes in Sea Level Resulting From Increased Atmospheric Carbon Dioxide," Changing Climate, 1983.
S. Hicks, H. Debaugh, and L. Hickman, Sea Level Variations for the United States 1855-1980, Rockville, MD: U.S. Department of Commerce, NOAA-NOS, January 1983.

IMPACTS OF SEA LEVEL RISE

The physical impacts of sea level rise can be divided into five categories: (1) inundation of low-lying area; (2) erosion of beaches, particularly along the open coast; (3) increased flooding and storm damage; (4) increased salinity of surface and ground water; and (5) higher water tables. Most of the land low enough to be inundated in the next century consists of wetlands, such as the salt marshes along the Chesapeake Bay, and various coastal estuaries, such as Sinepuxent and Chincoteague Bays near Ocean City. At the rate of sea level rise of thirty centimeters (one foot) per century as has occurred in the last century, most salt marshes can keep pace with the rising sea through sedimentation and growth of vegetation (Orson, Panageotou, and Leatherman 1985). However, they probably could not keep pace if the sea rose much more rapidly. In fact, a report by the U.S. Fish and Wildlife Service cites sea level rise as a cause of marsh loss at Blackwater Refuge on the Eastern Shore (Pendleton and Stevenson 1983).

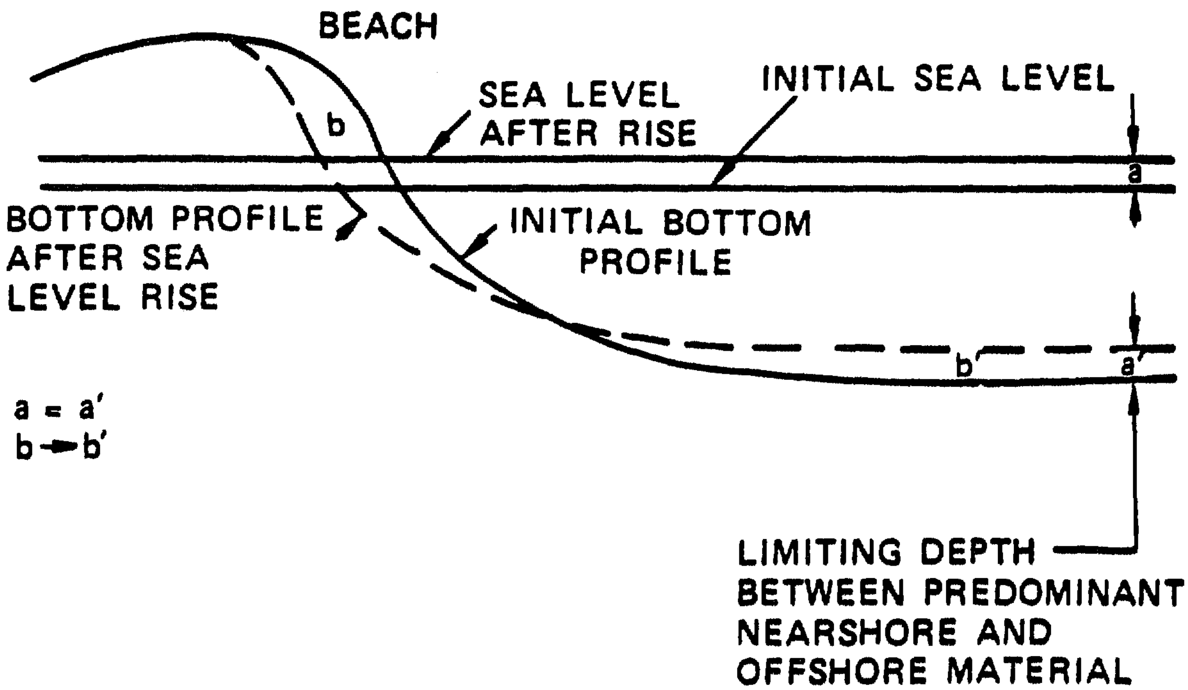
Although existing marsh would drown, new marsh could form inland. For example, Kana, Baca, and Williams (1985) estimate that Charleston, South Carolina would only lose 50 percent of its marshes with a one-meter rise, as long as people did not prevent new marsh from forming. However, development may prevent a landward migration of marshes and force these ecosystems to be lost. Decision makers might prefer to delay consideration of this issue until there is more certainty about future sea level rise. However, this strategy could make it impossible to avoid a future large-scale loss of coastal wetlands and property. Decisions being made today largely determine whether or not development will prevent marshes from forming inland. Most building codes, master plans, and zoning codes assume that once an area just inland of the marsh is developed, it will remain that way forever; but for wetland ecosystems to survive, these areas would have to become undeveloped once again.[11]

Sea level rise could also cause land that is above sea level to erode. Along the coast of Maryland, winter storms and occasional hurricanes erode the beach and deposit the sand off shore. Waves during calm periods "dredge" the sand off the nearshore bottom and redeposit it on the beach. Sea level rise results in a net erosion of the beach by allowing storm waves to strike further inland and by decreasing the ability of calm waves to rebuild the beach.[12] Figure 5 illustrates the upward and landward shift of the beach profile that accompanies sea level rise, commonly known as the Bruun Rule (Bruun 1962). Along most U.S. beaches, a thirty-centimeter (one-foot) rise in sea level would cause approximately thirty meters (one hundred feet) of erosion, although the actual amount depends on the wave climate and beach profile. Rather than erode in place, coastal barrier islands would migrate landward, as storms push from the ocean side to the bay side.

Perhaps the most economically important consequence of sea level rise would be increased flooding and storm damage. The direct impact of a one-meter rise in sea level would be to raise storm flood levels by one meter. However, several other indirect effects could further increase damages. Erosion from sea level rise would leave some coastal property more vulnerable to storm waves. Coastal stormwater drainage systems would operate

FIGURE 5

THE BRUUN RULE: A RISE IN SEA LEVEL CAUSES BEACH EROSION



If the sea rises one foot, so will the offshore bottom. The sand necessary to raise the bottom (area b') can be supplied by artificial beach nourishment or by waves eroding the upper part of the beach (area b).

Source: Adapted from Schwartz, 1967. "The Bruun Theory of Sea Level Rise as a Cause of Shore Erosion," Journal of Geology, 75:76-92.

less effectively. Finally, higher water tables and surface water levels would decrease natural drainage.

Other consequences of a greenhouse warming could also have impacts on flooding. Warmer temperatures would intensify the hydrologic cycle and increase worldwide rainfall by 10 percent or more (Rind and Lebedeff 1984). Although predictions for particular areas are not possible, rainfall would presumably increase in some coastal areas. Furthermore, because hurricanes require an ocean temperature of 27°C (79°F) to form (Wendland 1977), a global warming may extend the hurricane season or result in hurricanes forming at higher latitudes. However, hurricanes depend upon many other factors, all of which must be assessed before meaningful statements about future hurricane frequency will be possible.

EPA has investigated several possible responses to erosion and flooding caused by sea level rise. Gibbs (1984) estimates that the economic impact on Charleston, South Carolina, could be one to two billion dollars over the next century, but that anticipatory zoning and engineering measures could cut the potential losses in half. Webb and LaRoche examined the drainage systems of a watershed in Charleston. They concluded that a thirty centimeter (one foot) rise by 2025 would necessitate modifications (mainly additional pipes) to the drainage system that would cost $3 million to implement (Webb, LaRoche n.d.). However, if these modifications are incorporated into the planned overhaul of the system, the additional cost would only be $300,000.

The possible importance of salinity increases caused by sea level rise is poorly understood. The Delaware River Basin Commission has estimated that a thirteen-centimeter (five-inch) rise in sea level would cause the salt front in the Delaware River to migrate two to four kilometers (one to two miles) upstream. A rise of one meter could cause salt to move over twenty kilometers upstream, possibly threatening parts of Philadelphia's water supply, as well as aquifers in New Jersey recharged by the river (Hull, Titus, and Lennon n.d.). However, possible responses to such salinity increases have not been assessed, nor have the impacts on other estuaries.

Finally, a rising sea level would raise water tables. Flooding of basements and subway systems may be more frequent, necessitating additional pumps in some areas. No one has investigated the possible impacts on public sewer systems in coastal areas.[13]

OCEAN CITY CASE STUDY

Available research indicates that the impacts of even a one-foot rise in sea level would be important, but that the most adverse consequences could be avoided if communities take timely actions in anticipation of sea level rise. Unfortunately, most local governments do not have the resources to undertake sophisticated assessments of the potential implications. Regardless of the potential savings, the cost of undertaking a study is a hurdle that can prevent decision makers from considering the issue.

Development of low-cost erosion forecasting methods could substantially reduce the cost of assessing the impact of sea level rise. Although these methods lack the precision of more sophisticated analyses, their accuracy may be sufficient for long-range planning, where other variables such as economic growth and population are also uncertain.

To assess the potential for inexpensive assessments of sea level rise impacts, EPA contracted with three experts at low-cost erosion forecasts. This section describes the results of the three studies, each of which could be applied to other beach communities at a cost of $5,000-$10,000. Chapters 2 through 4 provide additional detail.

Present Trends

Like all ocean beaches, the beach at Ocean City exhibits a seasonal pattern. Winter storms erode the beach, while the calm waves of spring and summer rebuild it. In the long run, however, the shoreline has shown a slow but steady erosion trend. In the last fifty years, the beach has eroded over thirty meters (one hundred feet).

Leatherman (Chapter 2) and Everts (Chapter 3) offer very different explanations for the causes of this erosion. Leatherman argues that the erosion is caused by the long-term sea level rise of thirty-six centimeters (over one foot) in the last century. Everts estimates that substantial quantities of sand are being transported along the shore and off Fenwick Island, and that sea level rise is only causing 20 to 25 percent of the erosion. Leatherman acknowledges that alongshore losses are taking place, but suggests that the Delaware portion of the island, not Ocean City, is losing sand for this reason. Everts' perspective represents the general viewpoint of officials in Ocean City and the State of Maryland; however, Leatherman could also be correct if long-term sea level rise caused the alongshore transport of sand now observed.[14]

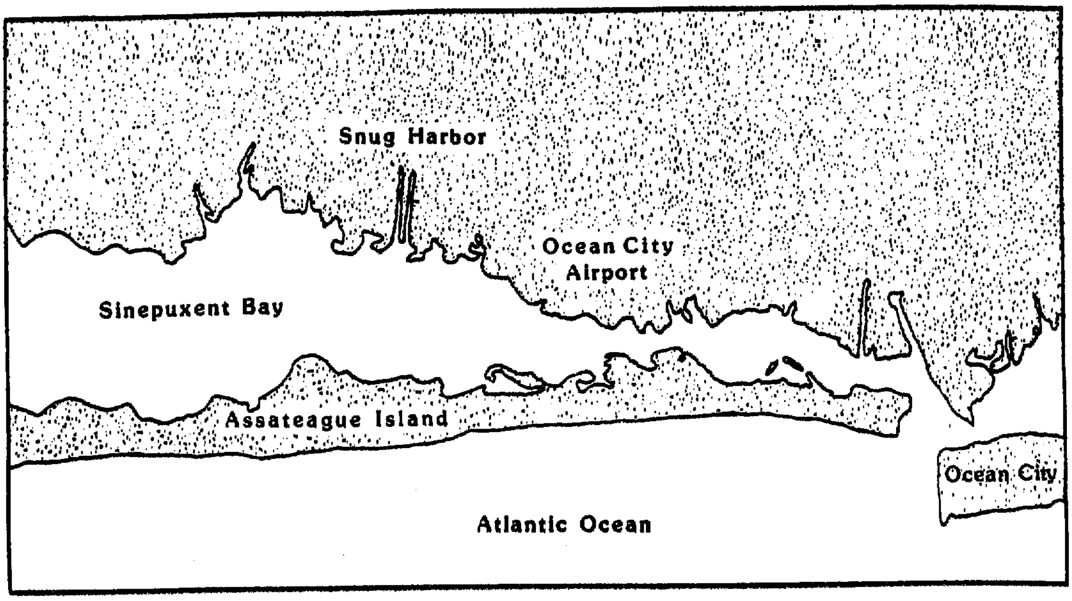
Another possible cause of the erosion could be the opening of Ocean City inlet (between Ocean City and Assateague Island) in 1933. A new inlet provides a sink for sand until tidal deltas (shoals) have been fully formed. Although the inlet was created by a hurricane, the construction of jetties along both ends has kept it open. It is generally recognized that the inlet and jetties have accelerated the erosion of Assateague Island to the south (Leatherman 1984),[15] which is illustrated in Figure 6; it is possible that they have also contributed to the erosion of Ocean City to the north.[16]

Leatherman examined maps of Ocean City's shoreline dating back to 1850, estimating that in the last 130 years the shoreline has eroded 75 meters (250 feet), which implies a retreat rate of 0.6 meters per year. However, the shore has not retreated by an equal amount each year. Everts points out that since 1962, the shoreline of Ocean City has retreated by only 0.2 meters per year, and the shore of Bethany Beach, Delaware (to the north) has been advancing 0.3 meters per year. From 1929 to 1962 on the other hand, the shore retreated at a rate of one meter per year.

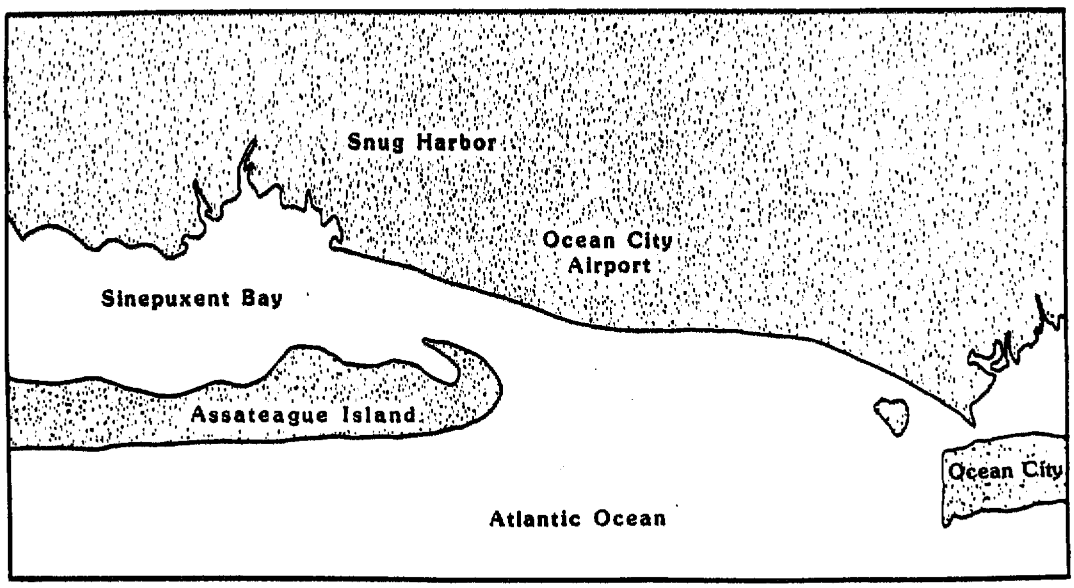
FIGURE 6

CURRENT SHORELINE AND PROJECTED EROSION AT ASSATEAGUE ISLAND, ASSUMING CURRENT TRENDS CONTINUE

1980 Shoreline



Projected Year 2000 Shoreline



Source: Revised from: Stephen P. Leatherman, "Shoreline Evolution of North Assateague Island, Maryland," Shore and Beach, (July) 1984, pp. 3-10.

In an appendix to Chapter 2, Bresee presents data showing the position of the shoreline and contours where the water is 10, 20, and 30 feet deep, for the years 1929, 1962, 1965, 1978, and 1979 at seventeen locations along the beach at Ocean City. Although coverage and season differed from year to year, it is possible to compare the data for 1962 and 1978 for the area south of 86th Street. Table 3 presents summary statistics of the erosion that has occurred during that time. Although the shoreline only retreated 9 meters (35 feet), the underwater portion of the beach eroded 35-45 meters (110-150 feet). In spite of the substantial variation of erosion along the shore, these results are statistically significant.

Leatherman points out that a continuous erosion rate would not be expected. Substantial erosion generally occurs during a major storm, with the calm waves gradually rebuilding (most of) the beach in subsequent years. Because there has been no major storm since the March 1962 northeaster (the worst storm on record), one would expect the shoreline to advance (or retreat more slowly). The slower rate of shoreline retreat does not necessarily imply that the entire beach system is eroding more slowly. The sand washing from off shore back onto the shore would generally imply that the offshore part of the beach system should be eroding more rapidly than the shore itself. For this reason, Leatherman uses the long-term rate of historical shoreline retreat in projecting future erosion.

Everts identifies human activities that may also be causing the visible portion of the beach to erode more slowly than the underwater portion. After the 1962 storm, the Corps of Engineers placed about one million cubic meters of sand on the upper part of the beach system. Furthermore, in the last several years, Ocean City has used bulldozers to push sand landward from the shore, expanding the visible portion of the beach at the expense of the underwater portion. Finally, groins may also tend to steepen the profile. If groins have their intended effect, they slow erosion of the upper part of the beach; however because they extend at most to the -10 foot contour, they do nothing to slow erosion of the rest of the profile.

The analyses by Leatherman and Everts imply that current observations of shoreline retreat may be causing people to underestimate the severity of current long-term erosion trends. If they are correct in concluding that the -20 and -30 foot contours have retreated substantially, a severe storm could restore the profile and cause severe erosion. In Chapter 4, Kriebel & Dean estimate the erosion that would result from a severe storm, using their storm climatology model, which accurately predicted the erosion that Hurricane Eloise caused along the coast of Florida. Kriebel & Dean project that a recurrence of the March 1962 northeaster (a 50-year storm) would cause the dune line to erode 20-35 meters (70-120 feet) for dunes with heights of 3.0-4.5 meters (10-14 feet). Even the presumably more imminent 10-year storm would cause 15 meters (50 feet) of erosion.

Future Projections

Table 4 summarizes the estimates of future erosion presented in Chapters 2, 3, and 4. For current trends, Leatherman's projections are more conservative than Everts' or Kriebel & Dean's. Leatherman estimates that the

TABLE 3

RETREAT OF THE BEACH AT OCEAN CITY, MARYLAND BETWEEN 21st AND 86th STREETS: 1962 to 1978[1]

Meters (feet)

	Shoreline	Contours -10ft	Contours -20ft	Contours -30ft[2]
Mean Retreat	9.1 (30.0)	40.0 (131.1)	46.1 (151.1)	34.4 (112.9)
Standard Deviation of Observations	17.0 (55.9)	26.5 (87.0)	35.3 (115.8)	62.7 (205.6)
Standard error of the Estimate of the Mean Retreat[3]	5.7 (18.6)	8.8 (29.0)	11.8 (38.6)	23.7 (77.7)
Statistical Confidence Level (CL) for The Mean Retreat Exceeding Zero (%)[4]	90≤CL≤95	99.5≤CL≤99.95	99.5≤CL≤99.95	90.0≤CL≤95
Statistical Confidence Level (CL) for The Mean Contour Retreat Exceeding the Mean Shoreline Retreat[5]	---	99.5≤CL≤99.95	97.5≤CL≤99	75.0≤CL≤80

1 Based on nine transects between 21st and 86th Streets. Transects at 3rd and 6th Streets are omitted because they are influenced by the jetty at Ocean City inlet.

2 Based on seven transects because data not available at 55th and 66th Street transects.

3 Estimated as the standard deviation divided by the square root of the number of observations.

4 Estimated using the t statistic: t = mean/standard error of the estimate.

5 Estimated using the reported differences in retreat rates for the contours and the shoreline for each transect. The hypothesis tested is that the mean difference in the retreat rates is zero.

TABLE 4

PROJECTED EROSION AT OCEAN CITY
Meters (Feet) of Shoreline Retreat Relative to its Current Position

	2000	2025	2050	2075
Current Trends				
Bruun[1]	4.9 (16)	11.0 (36)	17.0 (57)	23.0 (77)
Everts	21.0 (68)	46.6 (153)	72.5 (238)	98.5 (323)
Leatherman[2]	12.0 (39)	26.0 (85)	40.8 (134)	55.5 (182)
Kriebel & Dean	20.0 (66)	46.6 (153)	70.4 (231)	95.4 (313)
Mid-Range Low				
Bruun[1]	6.7 (22)	22.0 (72)	42.7 (140)	70.4 (231)
Bruun Adjusted[3]	23.0 (74)	57.6 (189)	98.1 (322)	147.0 (483)
Everts	26.0 (84)	72.5 (238)	132.0 (434)	215.0 (707)
Leatherman	20.0 (64)	55.5 (182)	105.0 (345)	174.0 (572)
Kriebel & Dean	22.3 (73)	54.9 (180)	92.7 (304)	_____ (460)
Mid-Range High				
Bruun[1]	12.0 (22)	32.3 (106)	62.8 (206)	105.0 (346)
Bruun Adjusted[3]	27.0 (90)	68.0 (223)	118.0 (388)	181.0 (593)
Everts	29.0 (95)	83.2 (273)	156.0 (511)	268.0 (878)
Leatherman	27.0 (89)	76.2 (250)	147.0 (483)	249.0 (813)
Kriebel & Dean	26.2 (86)	65.8 (216)	107.0 (353)	168.0 (550)

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[1] Bruun Rule is included for completeness. Because it includes only the impacts of sea level rise, it needs to be adjusted for alongshore and other losses in areas like Ocean City.

[2] Leatherman's estimates are based on shoreline maps dating back to 1850. If he had used only the period since 1962, his estimates would be much lower. He deemed the longer series more appropriate because the -10, -20, and -30 foot contours have continued to erode at the long-term rate of shoreline retreat.

[3] Bruun Rule Adjusted includes 2.6 feet per year due to factors other than sea level rise. Because 2.6 is derived from Everts, Bruun Adjusted is equal to Everts for current trends.

shore would erode 25 meters (85 feet) by 2025, whereas the other researchers estimate a retreat of about 45 meters (150 feet). However, he projects a greater increase in erosion due to sea level rise. Using EPA's mid-range low scenario (which is close to the National Academy of Sciences estimate), Leatherman, Everts, Kriebel & Dean, and our adjustment of the Bruun Rule project erosion in the 55 to 72-meter (180 to 238-foot) range for the 30-centimeter (1-foot) rise in sea level that would occur by 2025. For the mid-range high estimate, the four estimates range from 66 to 83 meters (216-273 feet). By 2075, the erosion estimates range from 140 to 215 meters for the mid-range scenario, and from 170 to 250 meters for the mid-range high scenario.

Because Ocean City's policy is to maintain its current shoreline, Everts and Kriebel & Dean also estimated the quantity of sand necessary to maintain the shore at Ocean City in its current location. Although Leatherman did not estimate sand requirements, we have calculated sand quantities implied by his estimates of shore retreat. As with the erosion projections, we have also adjusted Everts' application of the Bruun Rule to include alongshore losses of sand.

Table 5 displays the estimates of sand necessary to maintain Ocean City's shoreline through 2075, assuming that the beach profile remains the same on average. All of the estimates for the mid-range low scenario are in the range of 3-4 million cubic meters (4-5 million cubic yards) by 2000 and 8.4-10.0 million cubic meters (11-13 million cubic yards) by 2025. For the mid-range scenario, the estimates are 4.0-4.6 million cubic meters (5-6 million cubic yards) by 2025 and 10.0-12.2 million cubic meters (13-16 million cubic yards) by 2025. However, there is less agreement concerning what sand will be necessary if current trends continue. Kriebel & Dean's estimates are approximately twice that implied by the Leatherman analysis. This discrepancy is probably due to the fact that Kriebel & Dean assume that substantial sand will continue to be transported out of the area, whereas Leatherman assumes that on average, only sea level rise will cause a significant loss of sand. The Corps of Engineers Baltimore District notes that 2-3 million cubic yards of sand would be necessary to counter losses of sand without sea level rise.[17] To put these quantities into perspective, Kriebel & Dean estimate that about one million cubic meters would be necessary to protect against a 100-year storm that remained for 24 hours.

All of the methods yield estimates within a factor of two, except for the unadjusted Bruun rule, which is not designed for communities with significant alongshore losses of sediment. Although more sophisticated methods may yield more precise estimates, the estimates provided by the Leatherman, Everts, and Kriebel & Dean approaches may be adequate for first-order consideration of seal level rise impacts.

Because the focus of this study is beach erosion, not flooding, the researchers did not examine other impacts that may also be important to Ocean City or other coastal communities. These impacts might include bay-side flooding, wave damage, and the risk of inlet breach.

TABLE 5

SAND REQUIRED TO MAINTAIN CURRENT SHORELINE
(millions of cubic yards)

	2000	2025	2050	2075
	Current Trends			
Bruun[1]	1.0	2.2	3.3	4.6
Everts	4.0	9.3	14.0	19.0
Kriebel & Dean	4.8	10.5	11.4	22.5
Leatherman Adjusted[2]	2.4	5.2	7.8	11.0
	Mid-Range Low			
Bruun Adjusted[3]	4.6	12	20	29
Everts	4.6	11	19	28
Kriebel & Dean	5.5	13.3	22.1	33.2
Leatherman Adjusted	4.3	11	21	35
	Mid-Range High			
Bruun Adjusted	5.5	13	23	35
Everts	5.2	13	22	34
Kriebel & Dean	6.3	15	25.9	40.2
Leatherman Adjusted	5.6	15	29	48

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[1] Bruun Rule is included only for completeness. It is not intended to estimate erosion in areas with significant alongshore losses.

[2] Leatherman Adjusted is calculated by multiplying the ratio of Leatherman/Bruun estimates of erosion by the Bruun estimate of beachfill requirements.

[3] Bruun Adjusted is equal to Everts for current trends.

Implications

Ocean City's most important asset is probably its beach. Every weekend in the summer, approximately 250,000 visitors flock to this coastal town to swim and sunbathe. For this reason, state and local governments have recognized the beach as a resource that must be maintained. Because moving buildings back as the shore erodes is economically infeasible, the governments have opted for erosion control measures.

The expected rise in sea level will substantially increase the costs of these measures and change the relative merits of various shore protection strategies. But unlike many less densely developed coastal barriers, Ocean City's structures (and its stated policy of protecting its shoreline) need not be threatened by sea level rise. The high recreational and property values would economically justify shore protection for the foreseeable future.

The Corps of Engineers estimates that the first 4 million cubic meters of sand would cost approximately $26 million ($6.5 per cubic meter), that the next 5 million cubic meters would cost about $35 million ($7 per cubic meter), and that another 2.2 million cubic meters could be obtained for about $25 million ($11.2 per cubic meter) (U.S. Army Corps of Engineers 1980). Thus, the cost of maintaining the beach at Ocean City would be about $20 million through 2000 and $60 million through 2025 if the EPA mid-range low scenario (similar to the National Academy of Sciences estimate) are correct. Even if the mid-range high scenario occurs, the beach could be protected through 2025 for about $85 million.

Although these cost estimates are not negligible, the implied cost of $1-2 million per year is small when compared with the economic activity that takes place at Ocean City. At a rate of seven million visitors per year,[18] the cost of protecting Ocean City's shore would appear to be less than 30¢ per visitor. If sea level rises as projected, a beach protection plan would thus almost certainly be cost-beneficial. The Corps of Engineers estimated that the benefits from their proposed beach restoration would be $8 million per year, even though they did not consider accelerated sea level rise. The benefits from addressing the greater erosion that could occur with sea level rise would be much greater.

Ocean City and the State of Maryland have tentatively decided to build groins at a cost of $400,000 each, as an interim measure until the Corps beachfill plan is implemented. To the extent that current erosion is caused by sand moving along the shore and out of Ocean City, these groins might enable the city to "keep its own sand" and curtail erosion. However, groins do not prevent erosion caused by sea level rise (Sorensen, Weisman, and Lennon 1984). Although most of the researchers in Chapters 2, 3, and 4 believe that sea level rise is only causing one quarter of the erosion today, they all agree that if sea level rises as projected, it will gradually become the overriding factor. Thus, if sea level rises, pumping sand onto the beach will eventually be necessary. This sand, however, would bury the groins and shorten useful lifetimes compared to what previous analyses have indicated.[19]

Future sea level rise would also change the types of benefits gained by undertaking shore protection measures. For example, the Corps of Engineers determined that the benefits of their recommended beachfill plan would far exceed the costs; but because most of these benefits would be from increased recreational use of the beach, not flood protection, they did not consider the plan to have high priority. The prospect of sea level rise implies that without additional protection, much of Ocean City will become much more vulnerable to storm damage. Thus, the flood protection benefits of beach restoration may be much greater than previously estimated.

In the long run, sea level rise may imply that it will be wise to construct new buildings somewhat inland of what would otherwise be the preferred location. For example, it may be advisable to build parking lots on the seaward side of new high-rises, which would allow a builder to use the entire lot but leave the building less vulnerable to erosion and flooding (and the building would cast its afternoon shadow onto the parking lot, not the beach). The fact that Ocean City officials will probably always be able to justify expenditures for the protection of Ocean City's many large buildings does not mean that they should not look for ways of reducing the eventual costs. After the cheapest twelve million cubic meters of sand are exhausted, the costs may start to climb. Furthermore, if communities in Delaware follow Ocean City's example and attempt to keep their own sand, the amount of Delaware sand washing into Maryland would decrease.

The steepening beach profiles may increase the difficulty of forming a public consensus to address erosion and sea level rise. Ocean City may become increasingly vulnerable to storms as the greater part of the beach erodes; yet as long as the visible part remains stable, few property owners will feel threatened, even if tidal gauges and scientific reports show a rise in sea level. A major storm could disrupt this complacency, especially if, as Leatherman projects, substantial permanent erosion occurs. If major property damage also occurred, there would be many opportunities to adjust to sea level rise in the rebuilding phase.

The fundamental difficulty of planning for sea level rise is that the probability and magnitude of the phenomenon are uncertain. Nevertheless, it is a risk that should be taken seriously when people make decisions. Although we have less experience with sea level rise than with other factors such as storms, our understanding of the causes and our ability to predict the likely range are already greater for sea level rise than for many factors that are routinely considered in major decisions, including the severity of the next major storm.

Sea level rise is a risk against which some policies may provide more effective insurance than others. Although groins were determined to be more cost effective than was beach nourishment at controlling Ocean City's alongshore erosion, the latter would also control erosion caused by sea level rise, whereas groins would not. As with all insurance policies, coastal decision makers must weigh the costs and risks of various alternatives and decide on a case-by-case basis whether it is prudent to insure against the risks of sea level rise.

NEXT STEPS

A rising sea level could cause the beach at Ocean City to erode hundreds of feet in the next few decades if control measures are not taken. The cost of controlling erosion is likely to be tens of millions of dollars through the year 2000 and perhaps as much as sixty million dollars through 2025. Although the commercial and recreational resources of Ocean City could easily justify such expenditures, opportunities to reduce these costs should be investigated. Erosion control strategies, post-disaster policies, and long-term planning are all areas where ongoing efforts should consider the risk of future sea level rise.

Erosion control measures should probably have the highest priority. Standard analytic procedures can be employed to examine whether the risk of sea level rise warrants a reconsideration of current strategies. Delaying such an analysis could have substantial costs: every year the city and state spend hundreds of thousands of dollars on groins that may be subsequently buried if sea level rises.

Incorporating sea level rise into post-disaster policies could be very helpful. In the aftermath of a major storm, people will be much better educated about the risks of erosion and sea level rise; and an educated public is much more likely to support efforts that properly address these long-term risks. However, the need to act quickly may preclude the careful consideration necessary to adequately adjust to rising sea level. These policies must be formulated before the storm.

Finally, Ocean City's long-term planning should consider sea level rise. Over the next 50-100 years, rising sea level could have an impact on coastal areas as important as the sudden popularity of beaches that took place starting in the 1950s. Although sufficient sand has been identified to address erosion expected in the next forty years, the financial health of Ocean City in the longer run will require identification of additional low-cost supplies. The ultimate question for coastal barrier communities like Ocean City will be whether to raise the entire island in place as the sea rises, or to plan around a retreating shore. But sea level rise also has important implications for decisions involving building location and design, future population, roads, canals, and wetland protection.

Adjustments to sea level rise may not always be easy. But they are more likely to be successful if people start to plan while the phenomenon is still a future risk, rather than wait until it is a current reality.

NOTES

1. Expenditures of sport fishermen have increased from $3 billion in 1960-to $18 billion in 1980. Expenditures of hunters have increased from $1 billion to $9 billion over the same period.

2. The number of recreational boats in U.S. waters has increased from 8.8 million in 1970 to 13.2 million in 1983. Expenditures in 1983 were $9.4 billion.

3. PL 90-448, Section 1302

4. PL 92-53, 16 USC 1451, Section 303.

5. For Massachussets, see M.G.L. Ch. 131, S 40 Reg 310 C.M.R. 9.10(2) or Mass General Laws.

6. See: Clark, J.A., W.E. Farrell, and W.R. Peltier, 1978. "Global Changes in Post Glacial Sea Level: A Numerical Calculation." Quarternary Research 9:265-287. Note, however, that William Tanner of Florida State University suggests that there is a 3 percent chance that these factors could cause a rise or fall of one meter in a century. Personal Communication, William Tanner. Geology Department, Florida State University.

7. Studies on the greenhouse effect generally discuss the impacts of a CO_2 doubling. By "effective doubling of all greenhouse gases" we refer to any combination of increases in the concentrations of the various gases that causes a warming equal to the warming of a doubling of CO_2 alone. If the other gases contribute as much warming as CO_2, the effective doubling would occur when CO_2 concentrations have reached 450 ppm, 1.5 times the preindustrial level.

8. Robert Thomas, Jet Propulsion Laboratory, personal communication with John S. Hoffman, EPA.

9. Robert Thomas, Jet Propulsion Laboratory, personal communication with John S. Hoffman, EPA.

10. Computer printout underlying calculations from Seidel and Keyes, op. cit.

11. See: Titus, J.G., 1984. "Planning for Sea Level Rise Before and After a Coastal Disaster." In Barth, M.C. and J.G. Titus, op. cit.

12. The ability of waves to rebuild the beach is reduced in that a complete restoration of the original profile location would require the nearshore water depths to be greater than they had been before the sea rose. As sea level rises, so must the nearshore bottom.

NOTES (continued)

13. However, a town planner in Westerley, Rhode Island, estimates that a thirty-centimeter rise could contaminate over one hundred septic tanks along the town's shoreline. Griscom, Clement. Presentation to Rhode Island Sea Grant Conference on Sea Level Rise, November 29, 1984.

14. Sea level rise can contribute to alongshore transport if deeper water levels create sinks for sand in inlets and tidal shoals. Furthermore, unless slopes are uniform everywhere, sea level rise will tend to erode some areas more than others. The areas that erode the least will tend to later experience alongshore losses to areas that have eroded the most.

15. Conversations with local, state, national park, and Corps of Engineers officials, as well as citizen groups, indicate that most people believe that the jetty at the south end of Ocean City has filled with sand that would have otherwise washed onto Assateague. Robert Whalin, Director of the Coastal Engineering Research Center, however, states that recent research by his office shows that the jetties are not the only cause of erosion. Letter from Robert Whalin, Director of CERC, to James G. Titus, EPA, May 1985.

16. Although the predominant alongshore drift is to the south, the flow is occasionally to the north. During these periods, the inlet carries sand that would otherwise flow to Ocean City to shoals off shore.

17. Ed Fulford, Baltimore District, Corps of Engineers, letter to James G. Titus, EPA, May 1985.

18. Sandy Coyman, Town of Ocean City, Personal Communication.

19. Ed Fulford, Baltimore District, Corps of Engineers, letter to James G. Titus, EPA, May 1985.

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CHAPTER 2

GEOMORPHIC EFFECTS OF ACCELERATED SEA LEVEL RISE ON OCEAN CITY, MARYLAND

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INTRODUCTION

Coastal zones are inherently dynamic environments, being characterized by differing geomorphic processes and coastline configurations. To account for this wide variability in site and process, this study has combined analyses of historical trends and empirical approaches to model projected changes along Ocean City, Maryland. It evaluates the shoreline changes for a range of projected rates of sea level rise (baseline, mid-low and mid-high) at particular time periods (2025, 2050, and 2075).

Once digitized and transformed by a sophisticated shoreline mapping program, Metric Mapping (Leatherman 1983a), former shoreline positions portrayed on historical maps form the basis for projecting potential shoreline excursion rates as a result of sea level rise. These extrapolated rates can then be assessed in light of the possible impact that recent human modification may have on future trends.

This chapter first describes briefly the physical characteristics of the study area and then discusses projected shoreline responses to various EPA-derived sea level scenarios. It also contains an appendix describing the offshore changes associated with long-term sea level rise.

Sea level has always been rising or falling throughout geologic time relative to the land surface. The last major change in sea level occurred during the most recent Ice Age, when sea level was approximately 100 meters (three hundred feet) lower than at present. Although the rate of rise during the last several thousand years has apparently slowed, recent sea level changes based on tidal gauge data show a definite upward trend during this century (Fig. 1). Sea level may now be rising as fast as at any time during the last several thousand years (Gornitz, Lebedeff, and Hansen 1982).

An additional reason for concern over the recent rate of sea level rise is the increasing level of carbon dioxide in the atmosphere. If recent trends (largely resulting from the burning of fossil fuels) continue, some scientists believe that the atmospheric CO_2 could double in the next century. The National Academy of Sciences has estimated that this doubling will raise the earth's average surface temperature by 1.5°-4.5°C (Charney 1979). Other gases could double the warming from CO_2 alone.

The sea level rise scenarios were taken from Hoffman et al. (1983); nine rise/year combinations were selected from the projected sea level rise curves. Table 1 presents the algebraic sum of the projected sea level rise and subsidence to yield the relative sea level rise for Ocean City. The table indicates, for example, that absent any accelerated sea level rise (i.e., the baseline scenario), by 2025 sea level will have risen by 0.53 feet. In the mid-range low scenario, sea level will have risen by 1.13 feet by 2025. This amount of rise would inundate or otherwise dramatically alter low-lying coastal regions. Appendix I contains the nomenclature for shoreline interactions with sea level rise.

FIGURE 1

RECENT SEA LEVEL CHANGES ALONG THE U.S. COAST, BASED ON TIDAL GAUGE DATA (from Hicks 1978)

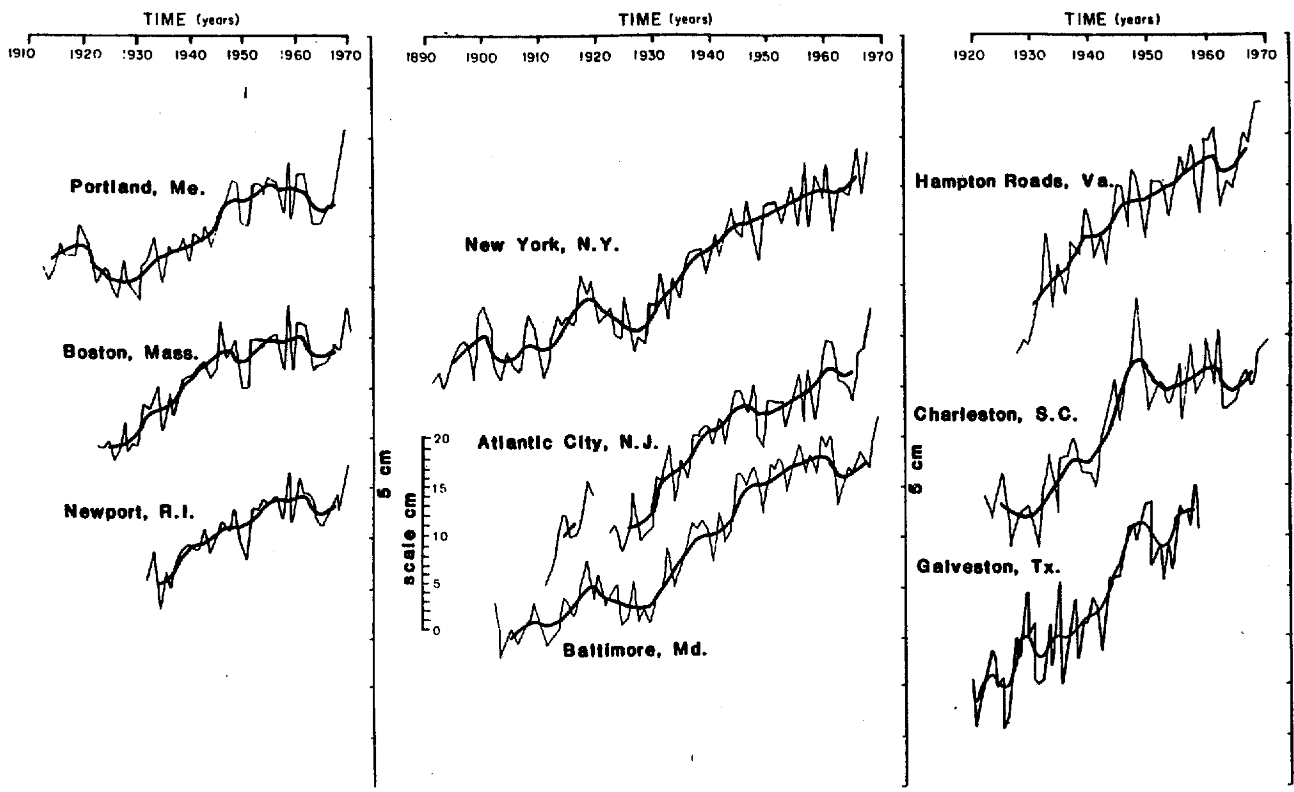

TABLE 1

RELATIVE SEA LEVEL RISE SCENARIOS CUMULATIVE RISE OVER 1980 LEVEL[1]

Time	Current Trend	Mid-Range Low Estimate	Mid-Range High Estimate
2000[2]	0.24 ft	0.40 ft	0.55 ft
2025[2]	0.53 ft	1.13 ft	1.55 ft
2050[2]	0.83 ft	2.14 ft	3.00 ft
2075[2]	1.13 ft	3.55 ft	5.05 ft

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1 Sea level rose 0.59 feet from 1930 to 1980, according to data from nearby tidal gauges (Hicks, Debaugh, and Hickman 1983) and interpolated using regional crustal deformation data (Holdahl and Morrison 1974).

2 These estimates, from the Environmental Protection Agency (Hoffman, Keyes, and Titus 1983), illustrate cumulative rise and include a 1.8 mm/yr local subsidence rate (1980 is the base year).

SITE DESCRIPTION

Ocean City, Maryland, is located on an Atlantic coastal barrier called Fenwick Island. It extends from the Delaware line to Ocean City Inlet (Fig. 2). Although Ocean City has been a resort community since the 1800s, it has experienced explosive growth during the last 15 years with the construction of high-rise condominiums (Fig. 3). The extensively developed barrier accommodates summer populations that often exceed 250,000 on peak weekends, although the permanent population is less than 6,000.

Although Ocean City has a tremendous economic investment in new real estate, there are only limited opportunities for reducing the potential of losing this existing development to flooding. Strong pressure will continue to be exerted for the continued development and redevelopment of Ocean City because of its established position as a major East Coast resort, its proximity to the major metropolitan areas of Washington, D.C., and Baltimore, Maryland (Humphries and Johnson, 1984), and because the National Parks Service owns the rest of Maryland's Atlantic Coast.

Barrier islands are dynamic landforms, subject to storm-surge flooding and sand transport processes. These coastal features are particularly vulnerable areas for human habitation, since they extend seaward of the mainland and are composed entirely of loose sediment (Leatherman, 1982). Coastal hazard planning on barrier island resorts, such as Ocean City, Maryland, often fails to recognize natural geological and geomorphic processes and their consequences on the built environment and related habitation. In defense of planning methods, coastal hazard analysis often suffers from lack of easily accessible and comprehensible data.

Physical Processes

Fenwick Island is characterized by low-lying topography fronting a shallow, microtidal embayment (Isle of Wight Bay). It is subject to flooding with even small rises in sea level. A slight vertical rise in sea level would result in significant horizontal displacement of the shoreline (Fig. 4). Also, storm surges superimposed on higher mean sea levels will tend to increase shoreline erosion, resulting in major economic losses.

The net transport of sand along the Atlantic Beach of Ocean City is to the south, although there are several reversals in this trend. The average annual net longshore transport is estimated to be 150,000 yd^3 (U.S. Army Corps of Engineers 1980). Since the stabilization of Ocean City Inlet with jetties in 1934-35, there has been a pronounced alteration of the adjacent shorelines for several miles in each direction. Updrift of the jetties at south Ocean City, a large amount of sedimentation has occurred. This shoreline progradation has necessitated the lengthening of the Ocean City fishing pier, and the north jetty is now impounded to capacity. A large portion of the sand moving southward in the littoral drift system is being swept seaward by the ebb tidal jet to form an enormous shoal (estimated volume is 8,000,000 cubic yards [Dean Perlin, and Dally 1978]). Since little of this sand is bypassing Ocean City Inlet, the northern portion of Assateague Island is being starved of sediment and pushed landward (Leatherman 1979).

FIGURE 2

LOCATION OF STUDY AREA ALONG THE DELMARVA PENINSULA

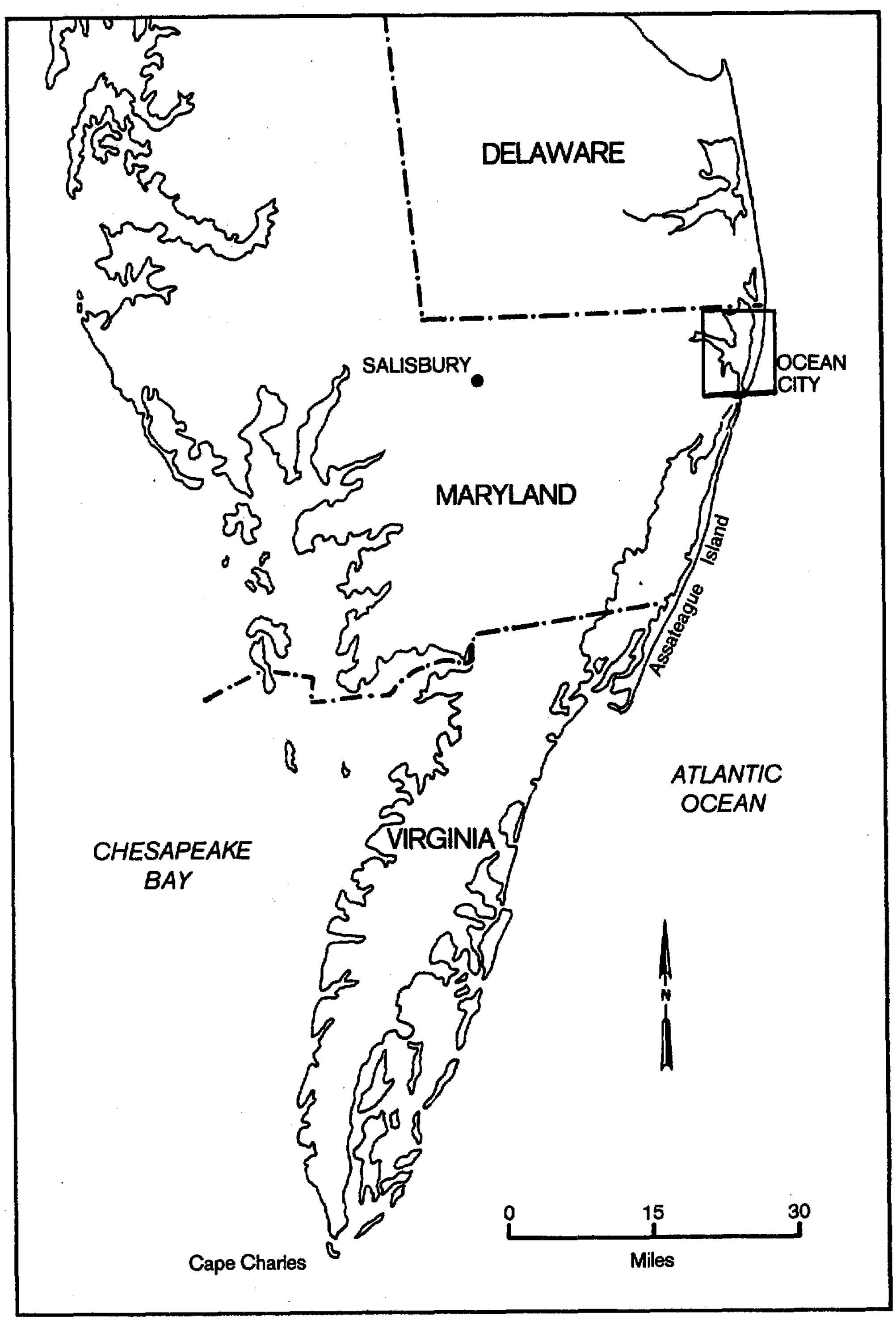
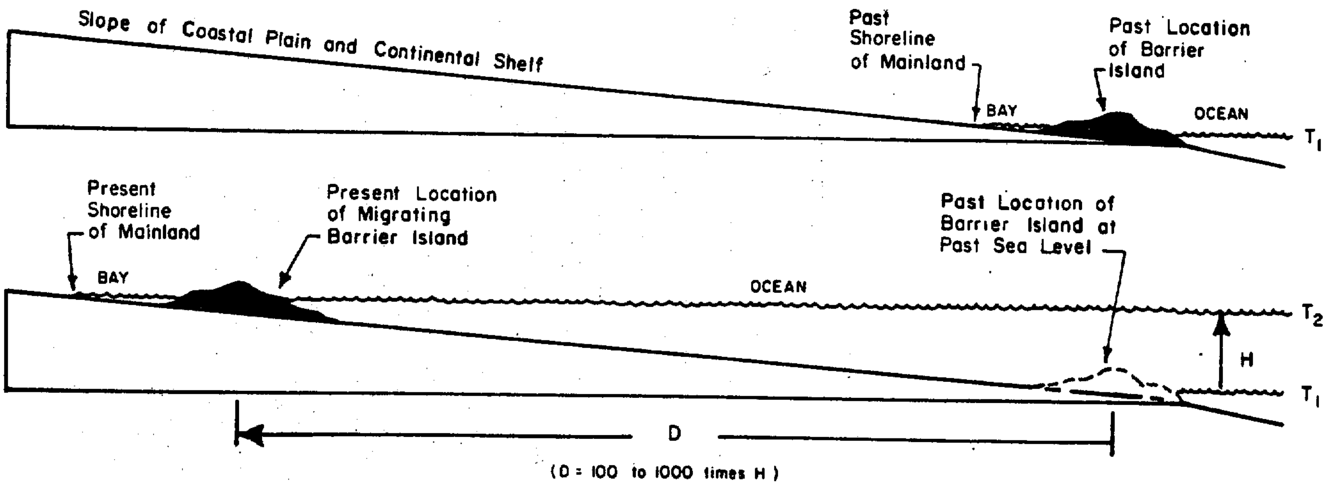


FIGURE 3

HIGH-RISE CONDOMINIUMS AND HOTELS HAVE BEEN
BUILT ONLY A FEW HUNDRED FEET FROM THE WATER'S EDGE
(1974 photograph near 100 St., Ocean City)

FIGURE 4

LANDWARD BARRIER MIGRATION UP THE GRADUALLY SLOPING COASTAL PLAIN OVER GEOLOGIC TIME WITH SEA LEVEL RISE



H = rise in sea level
D = horizontal migration of barrier island

T_1 = past sea level
T_2 = present sea level

ANALYSIS OF SHORELINE RESPONSE

Barrier islands, such as Fenwick Island upon which Ocean City has been constructed, change position and shape, depending upon the relationship between sand supply, wave energy, and sea level. Since there are essentially no new sources of sediment for the barrier beyond that already in the sand-sharing system or in transit through the coastal sector (littoral drift), shoreline position responds to storms, coupled with long-term changes in water level.

Although storms are responsible for major coastal alterations, it is not certain that storms in the absence of water-level changes could continue to alter the shoreline in an onshore/offshore direction. Wave-driven longshore transport, which would erode headlands and build spits or fill concavities, would continue to operate in any case, so that static shoreline conditions would never be achieved. However, beach stability in a two-dimensional sense (Bruun Rule; see Chapter 1, Figure 5) should theoretically be reached; Seelig (1982) has shown that beach equilibrium can be achieved under wave-tank conditions.

Perhaps a constructive way of viewing the allied roles of sea level sets the stage for profile adjustments by coastal storms. Long-term sea level rise places the beach/nearshore profile out of equilibrium, and sporadic storms accomplish the geologic work in a quantum fashion. Certainly major storms are required to stir the bottom sands at great depths off shore and hence fully adjust the profile to the existing water level. Therefore, our underlying assumption is that beach equilibrium will be the result of water-level position in a particular wave-climate setting.

Figure 5 illustrates the combined effects of erosion and submergence due to sea level rise. The term D_1 represents the landward translation of the shoreline due to a simple inundation of the land; the response time is instantaneous. Hence, direct submergence of the land occurs continuously through time and is particularly evident in coastal bays where freshwater upland is slowly converted to coastal marshlands. This change is termed "upland conversion."

The second displacement term, D_2, refers to a change in the profile configuration according to Bruun (1962). The Bruun Rule provides for a profile of equilibrium in that the volume of material removed during shoreline retreat is transferred onto the adjacent shoreface/inner shelf, thus maintaining the original bottom profile and nearshore shallow water conditions. Figure 6 is a more accurate depiction of this two-dimensional approach of sediment balancing between eroded and deposited quantities in an onshore/offshore direction without consideration of longshore transport. There can be an appreciable lag time in the shoreline's response to disequilibrium conditions.

Research along the Great Lakes may prove instructive in estimating response rates of shorelines to water-level changes. Due to climatic periods of dry and wet conditions, lake levels have fluctuated by as much as six feet in little over a decade. During 1969 lake levels again were high, resulting

FIGURE 5

SHORE ADJUSTMENT WITH SEA LEVEL RISE

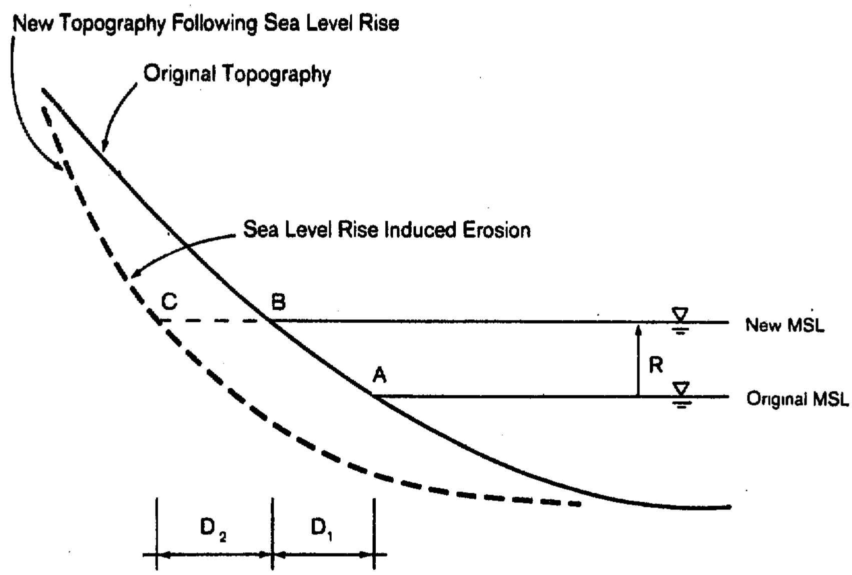
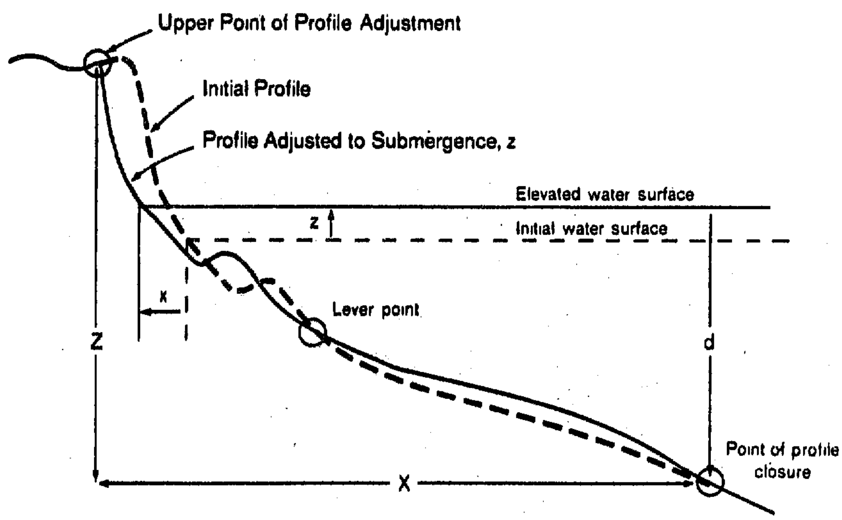


FIGURE 6

SHORE ADJUSTMENT TO CHANGE IN WATER LEVEL (after Hands 1976)



in significant erosion of sandy beaches and cliffs along many lake shores. The Great Lakes are not subject to astronomical tides to any degree, so that this complicating variable was eliminated. Hands (1976) found that the Bruun Rule is confirmed by field surveys of beach profiles during rising lake levels. The volume of sand eroded from the beach nearly matched off shore deposition. Hands (1976) also found that deposition extended off shore to a distance roughly equal to twice the height of a five-year storm wave. The lag time in shoreline response to lake level was rather rapid (approximately three years) because the lakes are subject to frequent storm activity in the fall and winter before surface icing.

The Great Lakes research may prove to be a useful analog in considering the response of open ocean shorelines to long-term sea level rise with qualifications. The Ocean City beaches are characterized by unconsolidated sandy sediments, which are easily mobilized during major storms. The extent of beach response depends only on the ability of waves to supply sufficient energy to the system to accomplish the required work (to obtain profile equilibrium in accordance with water-level position). Therefore, shore-response lag times are tied to storm intensity and frequency.

Along the mid-Atlantic Coast, both extratropical (northeasters) and tropical (hurricanes) storms are responsible for generating large waves capable of significant beach erosion. Ocean City is subject to several northeasters each winter, many of which cause moderately high tides and flooding. The March 1962 northeaster was more severe and damaging than any previously known storm to have affected the area. This winter storm was complex in structure and unusual in behavior (Bretschneider 1964). It produced a storm tide of 7.8 feet NGVD (National Geodetic Vertical Datum), since the wind-driven tides were superimposed on a high spring tide.

Hurricanes generally produce higher tides than northeasters but are much less frequent. The last hurricane of significance to affect Ocean City was Hurricane Donna, which occurred on September 12, 1960 (Table 2).

Figure 7 shows the tidal frequency curve for Ocean City, Maryland. Tidal elevations for storms with return intervals of between 5 and 500 years are shown. The annual frequencies of hurricanes and northeasters were determined separately and then summed to obtain the overall annual frequency at that level, as depicted on this graph (U.S. Army Corps of Engineers 1980). The lull in storm occurrence along the mid-Atlantic Coast during the past two and a half decades has corresponded with the period of major coastal construction. Ocean City expanded greatly in the early 1970s with the construction of high-rise condominiums and hotels. Therefore, Ocean City's beach profile is out of adjustment with sea level changes (by more than 25 years), and this trend will continue until the area is again directly affected by a major hurricane. Therefore, there is an appreciable time lag in shoreline response, depending upon the local storm frequency, which can only be dealt with statistically (at recurring intervals--a frequency/magnitude approach).

TABLE 2

MAJOR STORMS OF RECORD FOR OCEAN CITY, MARYLAND[1]

Storm	Type[2]	Storm Surge[3] (ft)	Damage Estimate
23 Aug. 1933	H	6.3	$ 500,000
21 Sept. 1938	H	?	minor
14 Sept. 1944	H	?	$ 250,000
12 Sept. 1960	H	?	$ 350,000
6-8 March 1962	N	7.8	$11,290,000

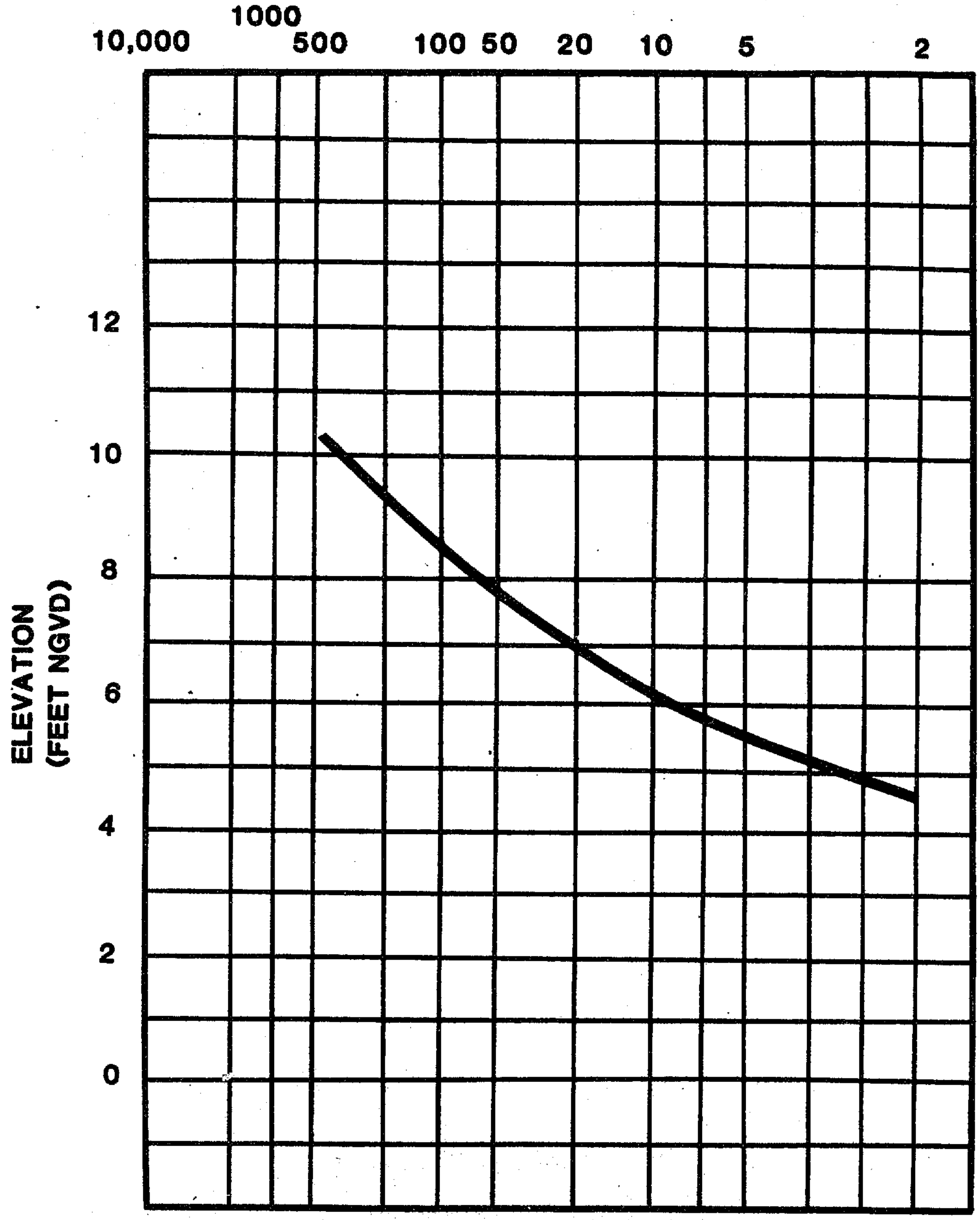
[1]From U.S. Army Corps of Engineers 1980

[2]Type: H = hurricane; N = northeaster

[3]Water level above NGVD.

FIGURE 7

OPEN-COAST STORM SURGE FREQUENCY
FOR OCEAN CITY, MARYLAND
(U.S. Army Corps of Engineers 1980)



METHODS

A shoreline mapping procedure, termed Metric Mapping, has been recently developed to quantify historical shoreline changes with a high degree of accuracy (meets or exceeds National Map Accuracy Standards) and relatively low cost (Leatherman 1983a). This automated technique has been designed to use the high-speed capabilities of a computer to simulate the best photogrammetric techniques. A flow chart depicting the steps involved in producing the computer-plotted maps is shown in Figure 8, and complete discussion of the procedure may be found in Leatherman (1984).

A large data set on historical shoreline positions (mean-high-water level) is available from the National Ocean Service. This information included U.S. Coast & Geodetic Survey charts (now called NOS "T" sheets) for the years 1849/50, 1908, and 1929/33, as well as vertical aerial photographs (1942, 1962/63, and 1977/80). Therefore, six sets of historical shorelines were available for the study area, spanning approximately the last 130 years (1850-80).

The Computer Mapping Laboratory of the University of Maryland's Department of Geography was used for shoreline data manipulation and plotting. The six shorelines were overlaid and plotted to scale on the computer-generated maps. Shorelines were differentiated by various dot-dash patterns. As a result of this research, the mapping program was further refined to provide rates of shoreline change. This refinement is not trivial, since shorelines are rarely straight; the base line for measurement must be at all places perpendicular to the shoreline to provide accurate information. Measurements are taken orthogonal to the measurement base line (or spine) at a preselected distance, where the spine is parallel to the shoreline. For each transect, a table of statistics on shoreline change is generated, and a summary histogram for each time period is prepared. From these data sets and summary statistics of the historic trend, a projection of future shoreline changes can be made.*

While this approach is less quantitative for modeling purposes than the Bruun method, it is more realistic in a geomorphic sense. The Bruun (1962) concept is essentially a two-dimensional approach, representing the sediment balance between eroded and deposited quantities in an onshore/offshore direction, without considering longshore transport. The technique used for this study involves the empirical determination of projecting new shorelines using trend lines. In this case, the shoreline response is based on the historical trend with respect to the local sea level changes during that time period. This procedure accounts for the inherent variability in shoreline response based on differing coastal processes, sedimentary environments, and coastline exposures (Leatherman 1983b).

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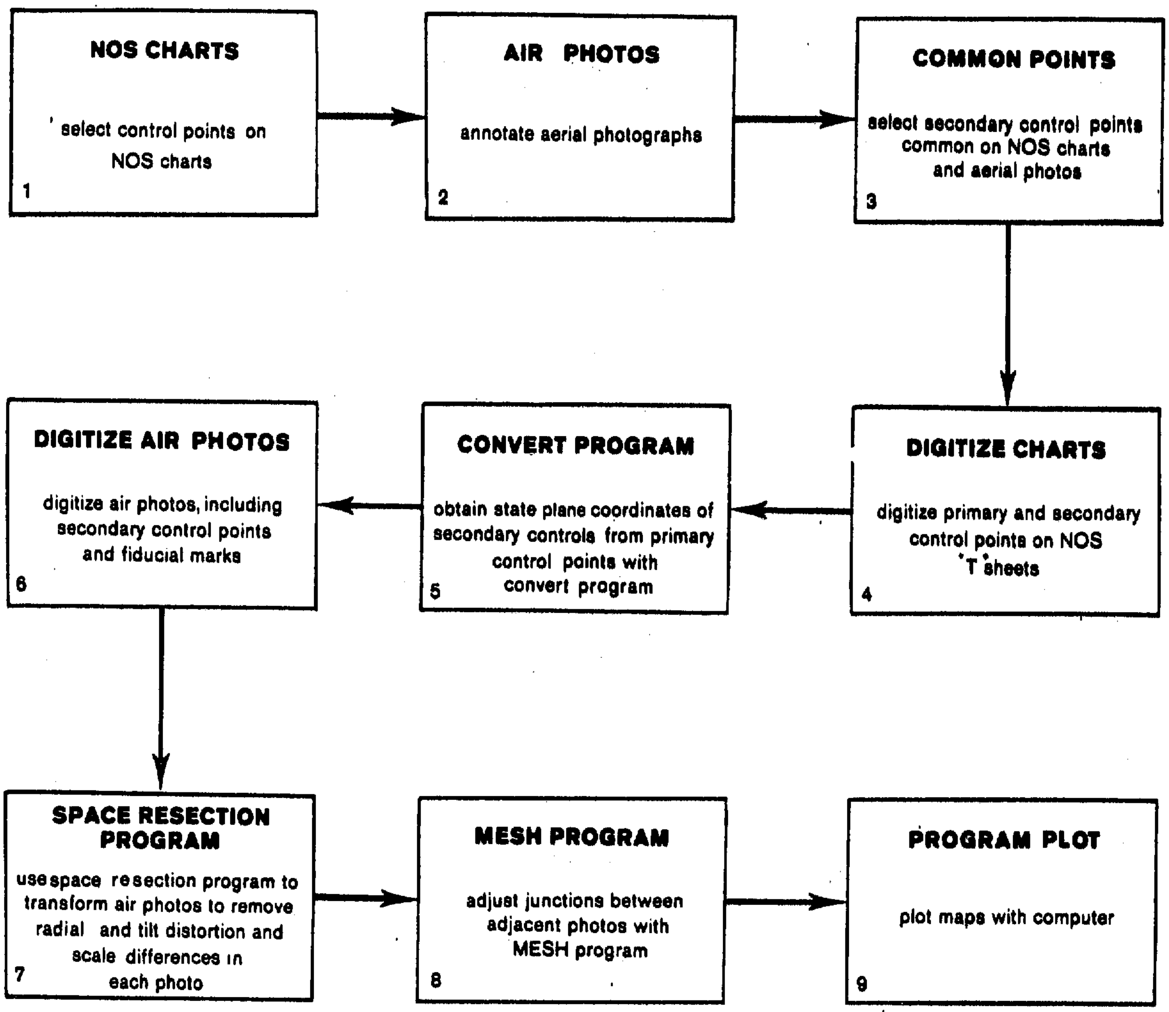
* This task was accomplished manually for this project, but we plan to write a computer program to simulate spatial changes in a temporal sense, using historical shoreline movements and physical relationships as the required inputs (Leatherman and Clow 1983).

FIGURE 8

METRIC MAPPING TECHNIQUE



The relationship between sea level rise and shoreline movement is formulated by assuming that the amount of retreat from the historical record is directly correlated with the rise rate of sea level. Therefore a 3X rise in sea level will result in a 3X increase in the retreat rate, assuming lag effects in shoreline responses are small compared to overall extrapolation accuracy.

Tidal gauge records document the local (eustatic effects plus isostatic effects, such as subsidence) rate of sea level change over the period of record. Records from nearby tidal gauges indicate that sea level rose about 0.59 feet between 1930 and 1980 (Hicks, Debaugh, and Hickman 1983). A portion of this apparent rise was probably due to subsidence. The relative sea level rise scenarios for baseline (current trend), mid-range low, and mid-range high include a 1.8 mm/yr local subsidence rate (Hoffman, Keyes, and Titus 1983).

RESULTS

Historical shoreline changes along Ocean City are shown in Figure 9. The average rate of oceanside erosion over the 130 years of record has been 1.9 feet per year, but there has been much variation along this shoreline. Histograms of shoreline change indicate some reversals of this trend, particularly at stations 1 through 13 (Figs. 10-13). This phenomenon could be due to large-scale, low-amplitude sand waves migrating downdrift along the shoreline. However, for most of the Ocean City shoreline, the overall trend has been long-term erosion (Fig. 14).

There are clearly gradients in the longshore transport of sand due to differential wave refraction and other effects that give rise to alongshore variations in shoreline trend (Goldsmith et al. 1974). Since the littoral nodal point for the Delmarva coastal compartment is believed to be located near Bethany Beach, Delaware (U.S. Army Corps of Engineers 1980), it can be assumed that over hundreds of years the littoral influx and outflux of sand at Ocean City should be approximately equal, except near the jetty. If this is correct, then the long-term losses of sand to the off shore, evident along the Ocean City shoreline, are due to historical sea level rise, which has averaged approximately 1.2 feet per century (Hicks 1978). Therefore, future shoreline location and erosion rates can be predicted on the basis of anticipated sea level rise (Leatherman 1983b).

From 1930 to 1980, the relative sea level rise was 0.59 feet (Hicks, Debaugh and Hickman 1983). This equates to 190 feet of erosion during the last 100 years with 1.18 feet of rise; thus, a 1-foot rise would correspond to 161 feet of erosion. Using the straight-line method of extrapolation as previously explained, then shoreline change can be projected for the nine rise/rate combinations (Table 3). The amount of shoreline recession varies from 39 feet (baseline) to 89 feet (mid-range high) for the year 2000 and from 182 feet (baseline) to 813 feet (mid-range high) by 2075. At present, the beaches along Ocean City are critically narrow, particularly during the high-energy winter months. Therefore, the current trend of recession exacerbates the problem and increases the vulnerability. Accelerated sea level rise increases the rate of retreat by two to five times, thereby

FIGURE 9

COMPARISON OF HISTORICAL SHORELINE CHANGES ALONG OCEAN CITY, MARYLAND (1850-1980)

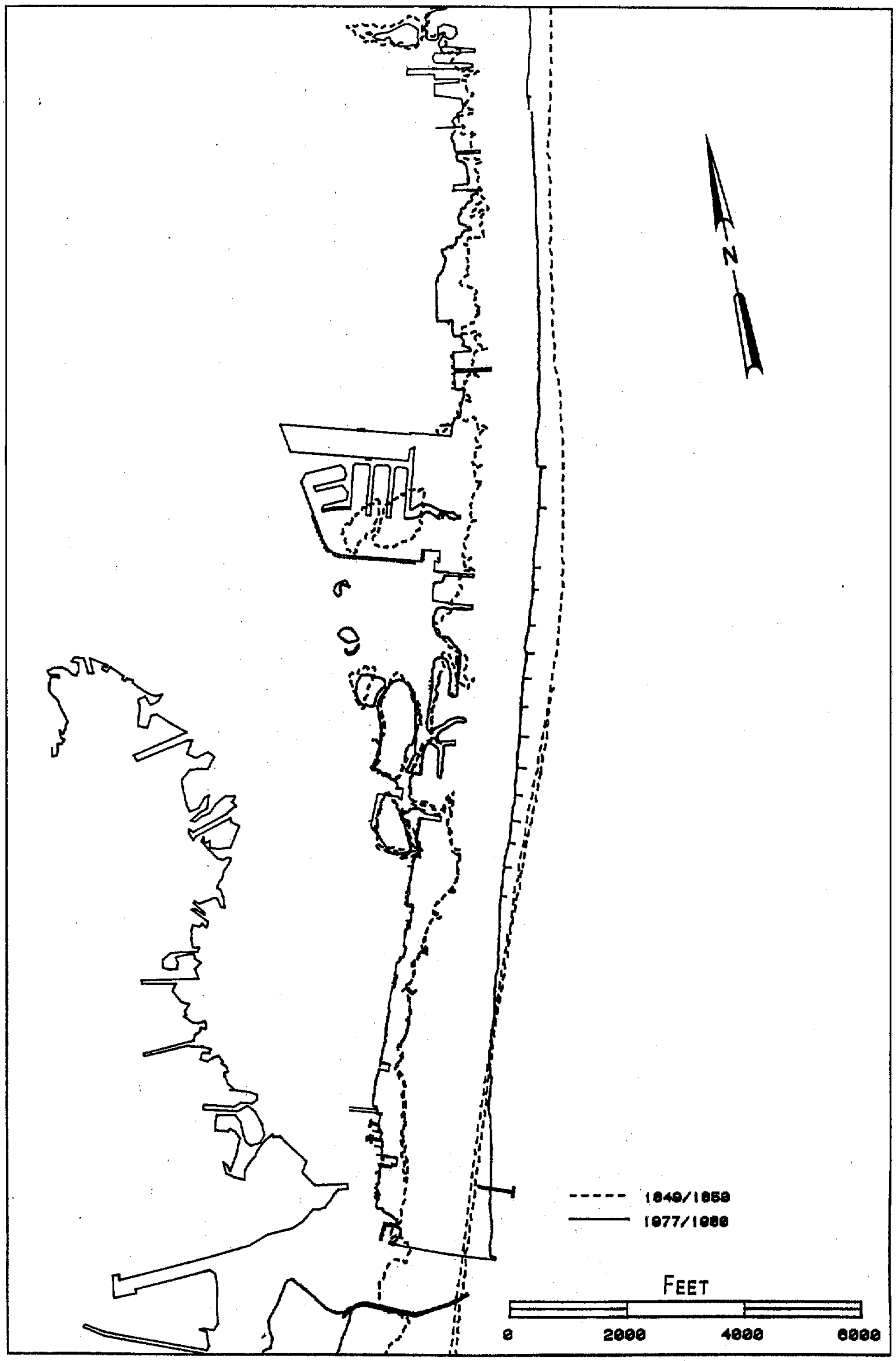


FIGURE 10. INDEX MAP OF OCEAN CITY SHOWING TRANSECTS USED BY PROGRAM THAT MEASURES SHORELINE CHANGES

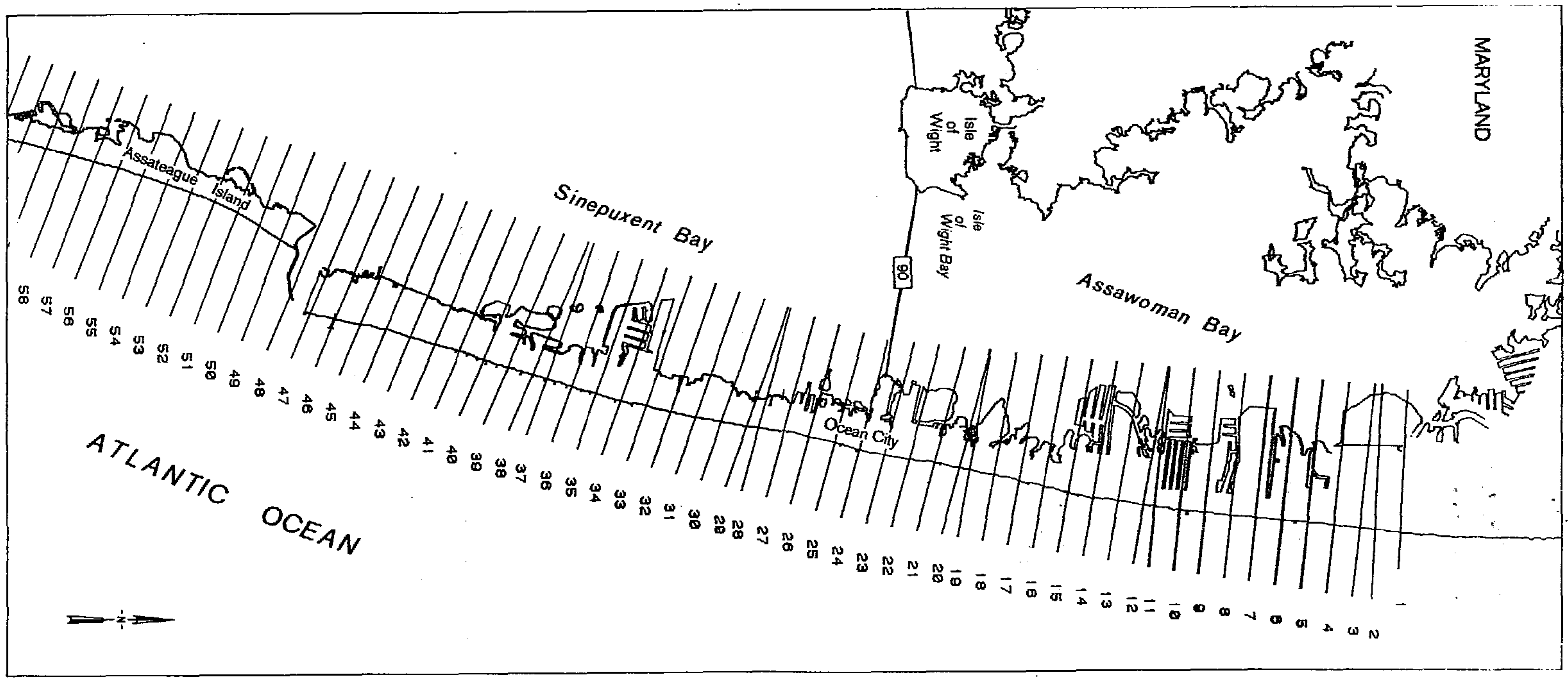


FIGURE 11

HISTOGRAM OF HISTORICAL SHORELINE CHANGES (1929-1942)
Transects 1 to 45 are Along Ocean City, Maryland.

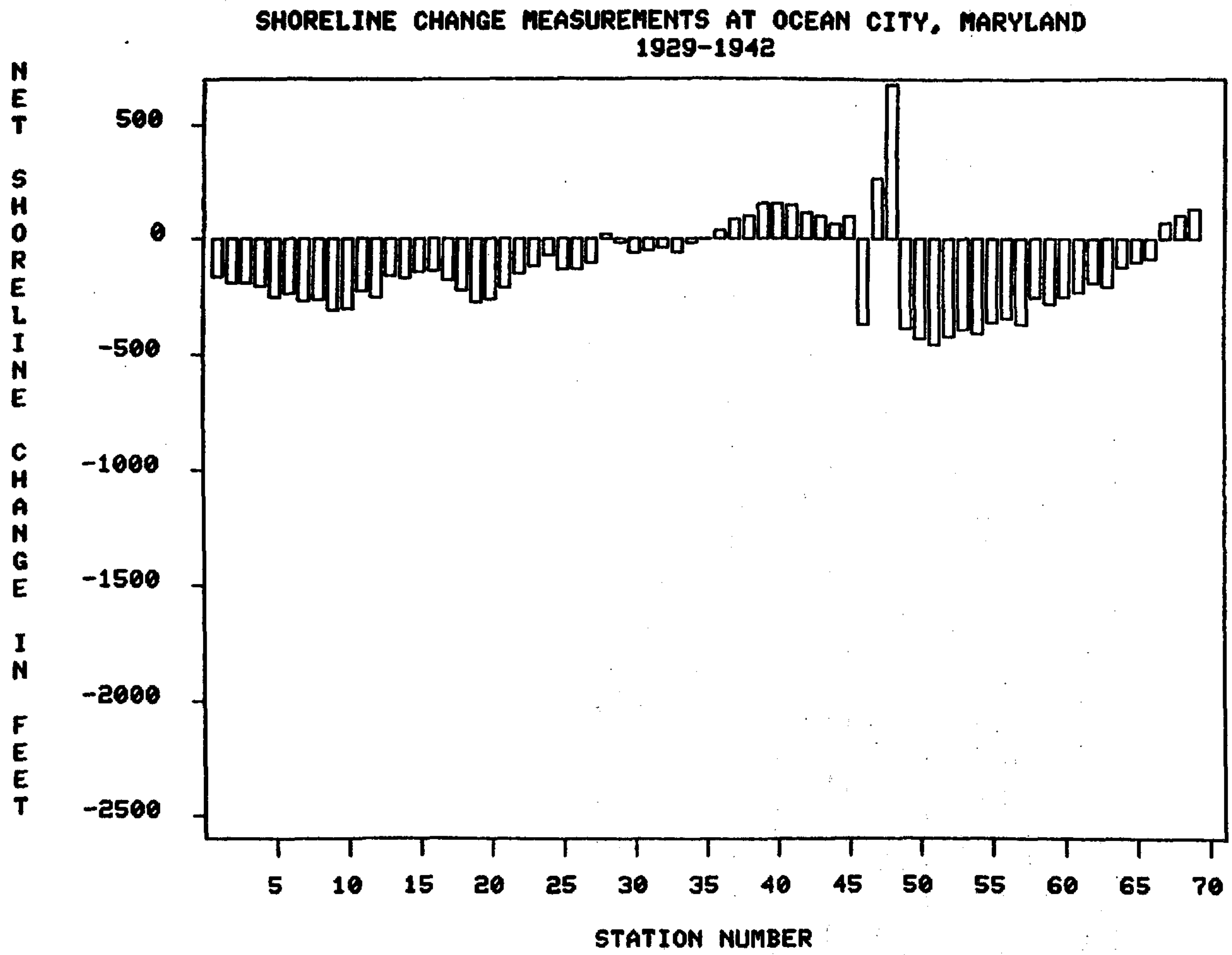


FIGURE 12

HISTOGRAM OF HISTORICAL SHORELINE CHANGES (1942-1962)
Transects 1 to 45 are Along Ocean City, Maryland.

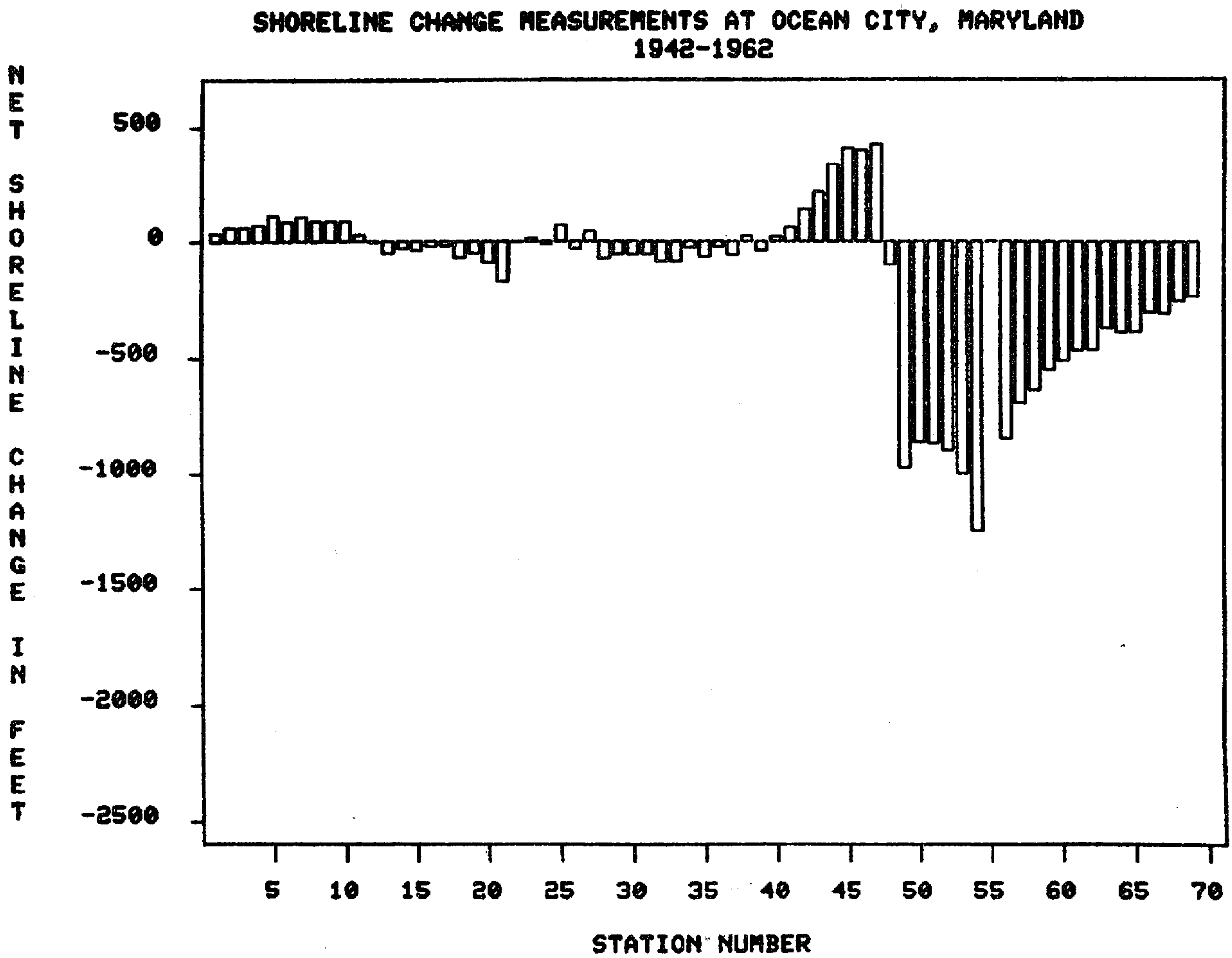


FIGURE 13

HISTOGRAM OF HISTORICAL SHORELINE CHANGES (1962-1980)
Transects 1 to 45 Are Along Ocean City, Maryland.

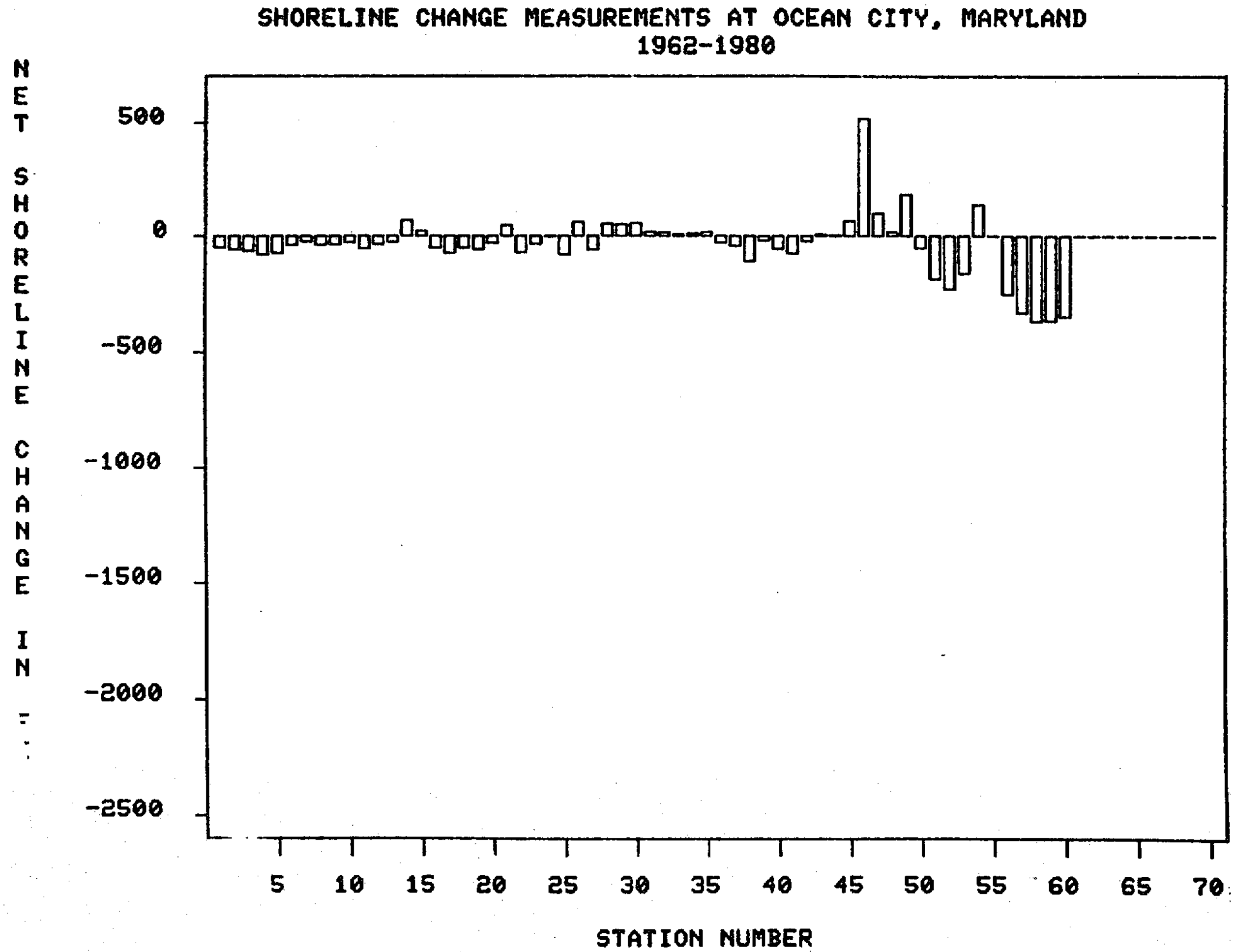


FIGURE 14

HISTOGRAM OF HISTORICAL SHORELINE CHANGES (1850-1980)
Transects 1 to 45 are Along Ocean City, Maryland.

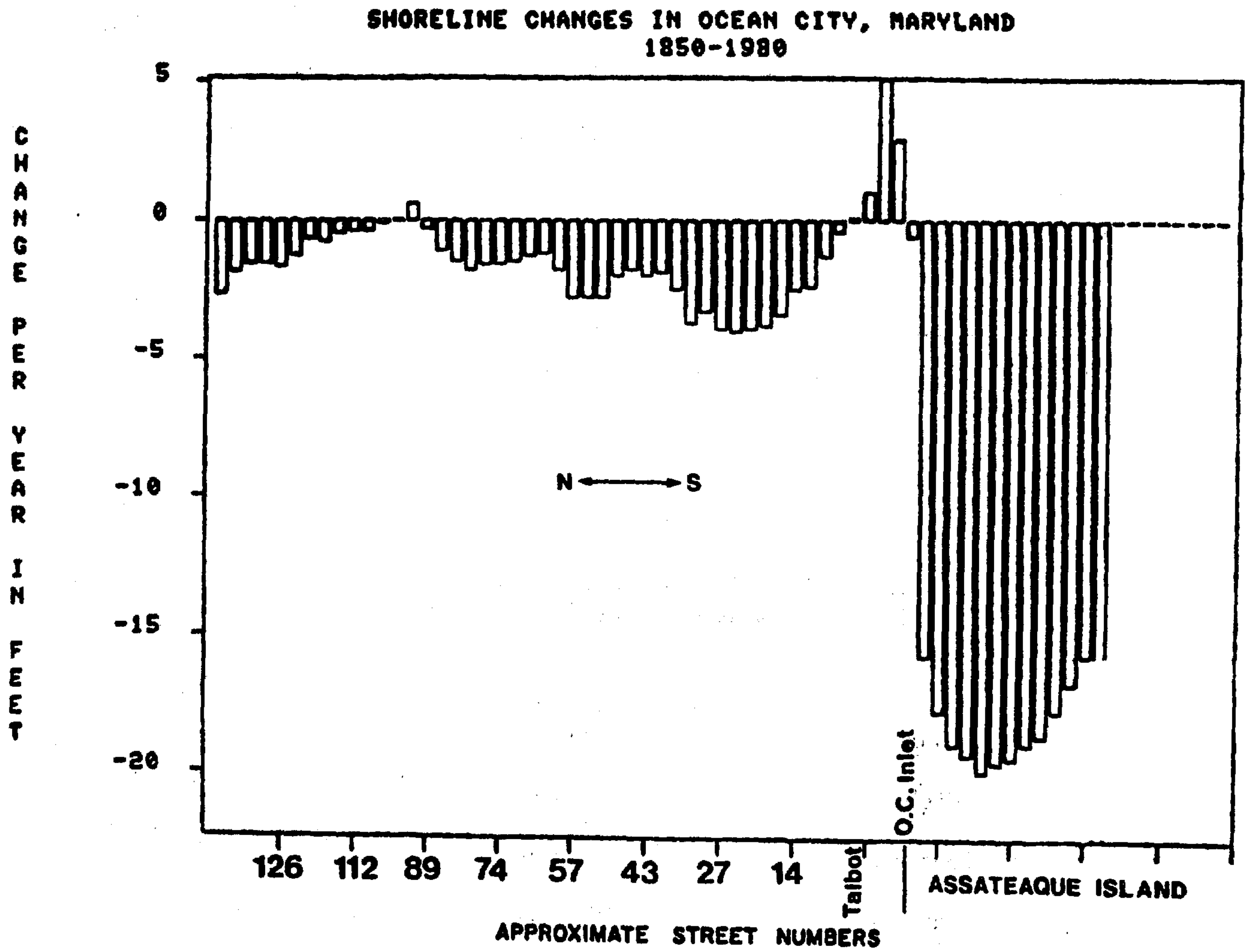


TABLE 3

PROJECTED SHORELINE RECESSION ALONG OCEAN CITY, MARYLAND[1]

Year	Current Trend	Mid-Range Low Estimate	Mid-Range High Estimate
2000	39 ft.	64 ft.	89 ft.
2025	85 ft.	182 ft.	250 ft.
2050	134 ft.	345 ft.	483 ft.
2075	182 ft.	572 ft.	813 ft.

[1]See Table 1 for rates of sea level rise.

TABLE 4

CONTOUR SHIFTS (1929-1965) From Trident Engineering (1979)

Contour	Over 36-Year Period	Average Shift per Year
Near High Water line	86 feet	2.4 feet
-10 foot contour	252 feet	7.0 feet
-20 foot contour	350 feet	9.7 feet

significantly reducing the planning time for hazard mitigation and significantly increasing the vulnerability of the urbanized area through time.

While the historical trend of recession has been set at 1.9 feet per year, there has not been an appreciable change in shoreline position since 1961/62 (Fig. 14). In other words, the historical rate of erosion has not been realized in the last few decades. This marked departure from the trend may be due to human modifications of the shore, notably groins, sand scraping, and some beach fill. However, it is more likely that the noted lull in hurricane activity since 1960 is the key factor.

This proposition is supported by an analysis of historical bathymetric changes. While these data are not as readily available as shoreline movement information, and their accuracy is more in question, significant trends emerge from a historical bathymetric comparison of the area off shore of Ocean City (Table 4). It is clear that the shoreface is steepening through time. The landward movement of the 20-foot-deep contour is greater than that of the 10-foot-deep contour, which in turn has migrated farther than the mean-high-water line.

We have conducted some checks of the Corps of Engineers' profiles, used by Trident Engineering (1979), as compared to the original Coast and Geodetic Survey boat sheets and have obtained similar measurements (Appendix II). It appears that the shoreline remains in approximately the same location for a period of time, while acting as a hinge as the adjacent shoreface steepens. It is not known at present what angle of shoreface inclination is the natural equilibrium orientation. Clearly, the current steepened condition cannot be considered at equilibrium, since recent bathymetric data have shown that the steepening trend has continued. Assuming that the equilibrium angle of inclination for the shoreface was reached at some point during the survey period (1850-1965), a future major coastal storm should cause the angle to decrease toward the idealized equilibrium position (Moody 1964).

It is a well established geologic principle that much geomorphic work is accomplished in quantum steps (Hayes 1967; Leatherman 1981 1982). Therefore, a major coastal storm would provide the impetus by shifting and redistributing nearshore sands to reverse the steepening trend of the shoreface. At this point, the shoreface returns to its minimum angle and then continues to slowly steepen again through time until the next major storm.

In summary, the shoreface appears to undergo bicyclic adjustment through time. A long, quiescent steepening phase, during which shoreline position is relatively stable or slowly retreating, is followed by a brief stormy period of shoreface flattening and rapid landward migration of the shoreline. Ongoing research should provide the type of data necessary to quantify this process and formulate a predictive model.

SUMMARY

The Atlantic Coast of Ocean City, Maryland, is undergoing long-term shoreline retreat as a result of sea level rise. During the past 130 years (1950-1980), the beach has eroded an average of 1.9 feet per year. Inspection of shoreline movement over this period shows that the recession is not constant through time or space. Indeed, there were periods of very rapid shoreline retreat, which probably corresponded to the major storms of record -- 1902, 1933, and 1962. In addition, the erosional trend at any one point along the shore has tended to fluctuate through time.

Many areas show reversals in trend, where an area that is characterized by high recessional rates for a period of time is later retreating more slowly, as compared to the overall trend, or accreting. These dramatic short-period (perhaps 20- to 30-year) trends may result from the alongshore migration of low-amplitude, very long wave length, sand waves. When the trough of the shoreline meander passes a certain locality, then it is characterized by erosion in excess of the trend. As the crest of the seaward-projecting horn of this crescentic feature passes the same point some time later, then the trend is reversed. Depending upon the amplitude of the sand wave and overall erosion rate, the area may be so affected as to actually exhibit pronounced accretion for a period of time. This appears as a flip-flop in the historical shoreline migrational record.

Analysis of these long-period sand waves can result in much confusion when we try to interpret short-term information, such as beach profiles. This analysis indicates that the longest accurate record available should always be used for determinating shoreline trend. Short-term data are useful in documenting site-specific and temporal changes, but such data are not the best indicators of net shoreline response over the long term.

This type of analysis could be undertaken for any sandy shoreline. The easily eroded unconsolidated sediments of barrier islands make the projections straightforward, except where modified by coastal engineering structures. The underlying assumption of this analysis is that shorelines will respond in similar ways in the future, as was the case in the past, since sea level rise is the driving function, and all other parameters remain essentially constant.

This analysis has assumed that total shoreline adjustments to sea level rise would be accomplished at the particular scenario year. Clearly, there will be some lag in shoreline response to higher water levels. This time period may be on the order of 25 to 50 years, corresponding to the frequency of major hurricanes. Better information on storm frequency and magnitude would improve this analysis. Without an in-depth analysis of site-specific data on many principal variables, such as offshore profile changes, the simple extrapolation of historical trends is a reliable technique for forecasting shoreline changes.

APPENDIX I

NOMENCLATURE FOR SHORELINE INTERACTIONS WITH SEA LEVEL RISE

As sea level rises, a number of complex and related phenomena come into play. In the following enumeration, we present general, intuitive definitions of the major phenomena and indicate the technical terms which most closely define each. A variety of shoreline interactions result from the rising (transgression) and falling (regression) of sea level. Most of these changes probably act in concert, but individually can be seen to result in several distinct responses. Rising sea levels are accompanied by general retreat of the shoreline. This is produced by erosion and/or inundation. Classically, erosion describes the physical removal of beach and cliff material, while inundation is the submergence of the otherwise unaltered shoreline.

During periods of falling (regression) or stable sea level, shorelines may advance seaward, or prograde, as material is deposited and accrete. Shoreline propagation generally occurs along river deltas, where sediment influx is high, unless the rate of sea level rise more than offsets sediment deposition. The recent dramatic erosion of part of the Nile Delta, resulting from the loss of sediment trapped behind the Aswan High Dam, reinforces the importance of sediment supply in maintaining shoreline equilibrium in deltaic environments. During at least the last century, there has been a significant rise in sea level which has resulted in pronounced shoreline recession along most Atlantic Coast beaches (e.g., Leatherman 1979, 1983b) and indeed along the large majority of sandy beaches worldwide (Bird 1976).

APPENDIX II

PROFILE CHANGES AT OCEAN CITY, MARYLAND: 1929-1978

by
Susan Bresee
Stephen P. Leatherman, Principal Investigator

Graphed profiles were available from the U.S. Army Corps of Engineers for the years 1965 and 1979. The profiles were drawn from seventeen transects, measured perpendicularly to the Ocean City coast. The origin and endpoint of each transect were digitized, along with four latitude and longitude values on each street map. From these given latitudes and longitudes, the coordinates for each transect were determined by computer. Thus, the four digitized rectilinear coordinates defined where the map was in space, and then the computer let it be known where the transects were, in terms of latitude and longitude, within that two-dimensional framework.

Map Bathymetry

After transects were determined from the 1965 and 1979 Ocean City street maps, the seventeen transects were hand plotted on each Ocean City map judged useful to the project. The other maps chosen were National Ocean Survey maps for 1929, 1962, and 1978. The 1848 and the 1849 maps were rejected because depth values did not reach the shoreline, original latitude and longitude markings were inaccurate, and values were measured sparsely parallel to the shoreline. Transect numbers are Ocean City street numbers.

Every value on the graphed 1965 and 1979 profiles was digitized. For the other maps, all values within rectangular envelopes 0.3 miles wide and 0.7 miles long centered along the sketched transects were individually digitized. each map was oriented in space by digitizing four map coordinates before transect values were digitized. A modified Surface II program retrieved each transect within its envelope of stored values. It extrapolated transect values from observed values and graphed each profile.

The inaccuracies of adjusting map scales and directionally stretching transposed maps were avoided (Sallenger et al. 1975). Since the transects and transect values were accurately determined and profiles were accurately graphed, many errors were eliminated. The largest errors remaining are mapping errors. For the purpose of slope measurement, extrapolation errors are not significant. Small irregular depressions or rises would not change profile slope calculations.

Table II-1 shows the position in feet of the shoreline and -10ft., -20ft., and -30ft. contours, with respect to an arbitrary origin. Table II-2 shows the changes between 1962 and 1978, the most recent interval for which the data permit a meaningful comparison.

TABLE II-1

CONTOUR DATA FROM 3RD STREET TO 145TH STREET
(in feet)

		Shoreline	- 10ft.	- 20ft.	- 30ft.
S3	1929	0	700	1370	1940
	1962	400	920	1490	2940
	1965	340	790	1350	--
	1978	400	900	1540	3250
	1979	390	740	1170	--
S11	1929	60	880	1340	1960
	1962	200	690	1210	2120
	1965	230	750	1320	2060
	1978	90	620	970	2330
	1979	120	520	800	1920
S21	1929	140	920	1300	2300
	1962	170	810	1030	1910
	1965	140	670	940	--
	1978	170	720	890	2000
	1979	140	450	690	1400
S26	1929	60	790	1320	2060
	1962	180	720	1070	2190
	1965	140	660	1050	1980
	1978	90	580	890	2190
	1979	110	520	810	1750
S33	1929	200	950	1460	2160
	1962	200	880	1140	2580
	1965	200	750	1070	2030
	1978	200	630	910	2600
	1979	220	480	780	1540
S41	1929	200	990	1550	2850
	1962	200	710	1420	3110
	1965	250	710	1180	2950
	1978	200	710	1180	2900
	1979	230	810	1210	2770
S48	1929	200	950	1400	3120
	1962	290	750	1260	3360
	1965	180	650	1120	3100
	1978	310	650	1080	2890
	1979	200	680	930	2040

TABLE II-1 (Continued)

		Shoreline	- 10ft.	- 20ft.	- 30ft.
S55	1929	220	980	1680	3320
	1962	220	780	1120	--
	1965	180	720	1070	2510
	1978	220	740	1130	--
	1979	220	530	920	2410
S65	1929	280	950	1520	--
	1962	200	810	1540	2630
	1965	220	720	1320	2540
	1978	220	640	1340	--
	1979	220	670	1420	2700
S76	1929	310	1080	1850	2920
	1962	120	720	1170	2730
	1965	150	590	1060	2630
	1978	10	470	900	2770
	1979	150	470	780	2260
S86	1929	170	900	1740	--
	1962	110	640	970	2950
	1965	140	670	1000	2930
	1978	0	380	1040	2690
	1979	140	480	890	2650
S94	1929	80	830	1260	3330
	1965	150	620	1010	2100
	1978	-	-	--	--
	1979	120	460	800	1780
S100	1929	250	940	1390	--
	1965	250	610	1070	2400
	1978	10	460	1030	1870
	1979	150	480	860	1780
S119	1929	230	1030	1430	2390
	1965	280	730	1150	2330
	1978	180	720	1030	2330
	1979	180	590	880	1550
S129	1929	250	960	1440	2420
	1965	150	570	1120	--
	1978	180	460	880	2550
	1979	150	400	670	1190

TABLE II-1 (Continued)

		Shoreline	- 10ft.	- 20ft.	- 30ft.
S137	1929	150	830	1190	2820
	1965	180	639	850	1770
	1978	110	430	730	1970
	1979	140	490	720	1320
S145	1929	180	800	1150	1610
	1965	120	480	740	1320
	1978	0	470	800	1510
	1979	140	450	740	1230

TABLE II-2

CHANGE IN THE POSITION OF THE SHORELINE AND -10, -20, AND -30 FOOT CONTOURS FROM 1962 TO 1978[1]
(3rd Street to 86th Street)

Transect	Shoreline	Contours -10ft.	Contours -20ft.	Contours -30ft.
S3	0	- 20	+ 50	+310
S11	-110	- 70	-240	+210
S21	0	- 90	-140	+ 90
S26	- 90	-140	-180	- 0
S33	0	-250	-230	+ 20
S41	0	0	-240	-210
S48	+ 20	-100	-180	-470
S55	0	- 40	+ 10	NA[2]
S65	+ 20	-170	-200	NA
S76	-110	-130	-270	+ 40
S86	-110	-260	+ 70	-260
mean	- 34.6	-115.5	-140.9	- 30.0
mean-adjusted[3]	- 30.0	-131.1	-151.1	-112.9

[1]Negative numbers indicate retreat toward the land.

[2]NA = not available.

[3]Exludes transects S3 and S11 which are influenced by the jetty at Ocean City Islet.

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CHAPTER 3

EFFECT OF SEA LEVEL RISE AND NET SAND VOLUME CHANGE ON SHORELINE POSITION AT OCEAN CITY, MARYLAND

by

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ABSTRACT

An estimate of the impact of past and future sea level rise on the shoreline of Ocean City, Maryland, is developed in this report. Two predictive methods are tested on a historical data set for 1930-80 and used to project future erosion through 2075. These methods are also used to project future requirements for beach nourishment.

Data consisted of analyzed title records, EPA-supplied global sea level rise projections, the local land subsidence rate at Ocean City, the net rate of sand loss by alongshore transport, the net rate of sand loss at the base of the shoreface and landward to the barrier island by overwash, wind, and ephemeral inlet processes, volumes added by beach replenishment, shoreface and barrier island profiles, and the size distribution of sediment landward of the shoreface.

The average measured shore retreat for the period 1930-80 was 176 ft, during which sea level rose 0.6 ft along the coast of Ocean City. Everts' (1984) method predicted a retreat of 184 ft with 19 percent due to sea level rise and 81 percent resulting from sand losses from the shoreface. Alongshore losses accounted for 88 percent of the net sand loss; losses to linear, shoreface-connected ridges at the base of the shoreface accounted for 9 percent. Bruun's (1983) method predicted a shoreline retreat of 43 ft with 91 percent of that value attributed to sea level rise. The Bruun method is not designed to consider shore retreat resulting from alongshore sediment losses.

The methods were also used to project future shoreline retreat, using sea level rise projections from Hoffman et al. (1983). These projections imply that a rise of 1.1-1.6 feet by 2025 and 3.6-5.0 feet by 2075 along the coast of Ocean City is most likely. The Bruun method projects that the shore will retreat 72-106 ft by 2025 and 236-346 ft by 2075, if no additional measures are taken to control erosion. The Everts method projects a retreat of 238-273 ft by 2025 and 707-878 ft by 2075. Shoreline retreat resulting from sea level rise, with one realistic exception, can only be reduced or stopped by beach nourishment, i.e., the periodic addition of sand from outside the shoreface system. The exception, which would reduce, but not eliminate, the retreat, is a shore-parallel dike that perches the shoreface and reduces its length. That portion of shoreline retreat caused by sand losses from the shoreface may, in addition to beach nourishment, be reduced by structural means. For example, seaward-directed sand losses may be reduced using offshore breakwaters, especially near the linear, shoreface-connected ridges. Landward-directed sand losses by overwash, aeolian transport and island breaching during extreme storms may be reduced with artificial dunes. Sand losses caused by longshore transport may be substantially reduced by a system employing a sand trap near Ocean City Inlet and a backpassing procedure to return the sand to the divergence nodal reach near the north end of Ocean City. The Bruun method implies that a beach nourishment solution would require 1.5-2.4 million cubic yards of sand through 2000 and 4.5-6.5 million cubic yards through 2025. The Everts method projects that 4.6-5.2 million cubic yards of sand will be necessary through 2000 and 11.3-12.9 million cubic yards through 2025.

INTRODUCTION

Moffatt & Nichol, Engineers, was requested to: (1) calculate shoreline retreat to year 2075 at Ocean City, Maryland, and (2) estimate the quantity of sand that will be necessary to maintain the current shoreline to year 2075. Two methods were used: (1) Bruun's (1962, 1983) method, and (2) Everts' (1984) method.

METHODOLOGIES

Bruun's (1962, 1983) Method

In 1962 Bruun proposed a method to predict the effect of a rising relative sea level (RSL) on a sandy shoreline. He assumes the Inner-Continental Shelf profile will maintain a constant shape and position relative to the sea surface by translating landward and up as RSL rises (Fig. 1). To accomplish this, Bruun maintains the beach and upper shoreface profile will erode and the lower part of the shoreface profile will acquire an equal volume of sediment. Furthermore, he assumes a point of intersection of the initial profile and subsequent profile (Fig. 1) will always exist.

Using the assumptions that (1) beach and offshore profile equilibrium exists and (2) the shore in question is in a state of quantitative materials balance, Bruun (1962) determined the practical approximation of shoreline movement, s (Fig. 1), to be

$$s = \frac{a\ell}{h} \qquad (1)$$

in which a = RSL rise, h = maximum depth of exchange of material between the nearshore and the offshore, and ℓ = length of the profile of exchange. The cross-sectional area produced by the upward movement of the profile, a, equals the area swept by the landward movement of the profile, sh. In 1962, Bruun did not consider balanced sediment transport into and out of the system a necessity for his method to work, and emphasized that the relationships of Equation 1 must be considered long term and regional in scope.

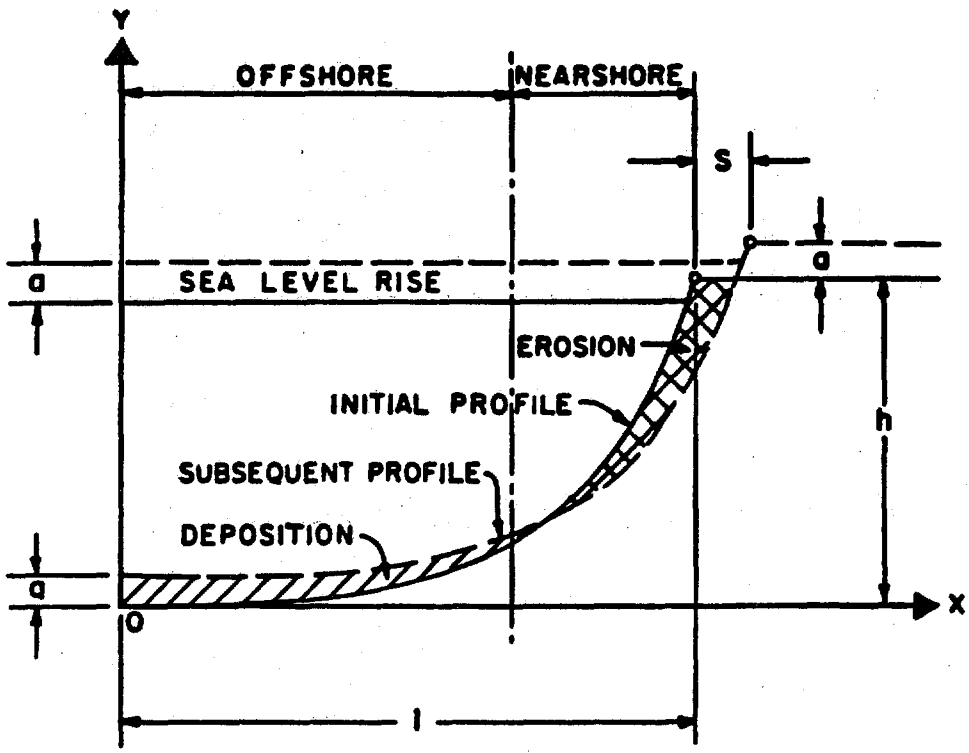
In 1983, Bruun discussed the effect of sediment composition on shoreline change. Where r = percent of material smaller than 0.06 mm (i.e., silt and mud-sized material), which is eroded from the nearshore area (Fig. 1), Bruun adjusted Equation 1 such that

$$s = \frac{a\ell}{h}\left(1 + \frac{r}{100}\right) \qquad (2)$$

The requirement for including this materials restriction is based on Bruun's assumption that very fine material produced in the eroded nearshore zone will not remain on the equilibrium profile in the depositional offshore zone.

FIGURE 1

DEFINITION SKETCH, BRUUN'S (1962, 1983) METHOD



For a narrow continental shelf, Bruun (1983) also introduced a loss function R to account for sediment transport beyond the outer edge of the offshore region. He cited submarine canyon losses as an example. To account for this (percent) loss seaward of the offshore boundary, Equation 2 was modified as follows:

$$S = \frac{a\ell}{h}\left(1 + \frac{r}{100}\right)\left(1 + \frac{R}{100}\right) \qquad (3)$$

Everts' (1984) Method

This is a sediment budget analysis which considers absolute losses and gains of sand to a bounded coastal reach. It is coupled with a procedure that accounts for the apparent loss of sand that occurs as sea level rises relative to the beach and shoreface. The dependent variable is shoreline position; independent variables are the RSL rise rate, shoreface and backbeach profile, percent of sand in the sediment deposit landward of the shoreface, and net losses and gains of sand from the shoreface and backbeach area (control volume).

Everts (1984) assumes, as Bruun (1962, 1983) did, that the shoreface will remain in equilibrium with the sea surface and move vertically upward as sea level rises. He also assumes no change in profile shape will occur during the rise. An accretional volume of sand-sized sediment, V_g and/or V'_g, as shown in Figure 2, is required by continuity to move the profile in space. The most likely source of that sediment is the volume, V_1, eroded as the shoreface profile translates landward and/or upward. An absolute addition or subtraction of sand, V_o, may also move to or away from the shoreface by transport across its boundaries, herein called a control volume. The sediment balance required to maintain an equilibrium shoreface profile becomes

$$kV_1 + V_o - (V_g + V'_g) = 0 \qquad (4)$$

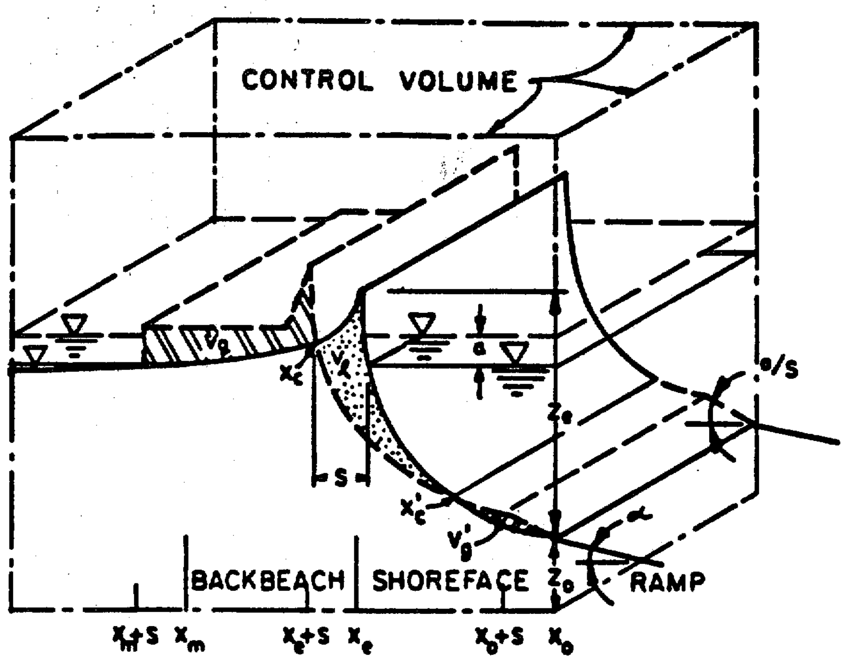
in which k equals that portion of liberated sediment in V_1 that is of sand size or larger.

Sediment volume changes in Equation 4 not caused by a redistribution of sand on the shoreface as the shoreface retreats are considered in the V_o term. This term accounts for spatial gradients in various components of sediment transport through the control volume and includes beach replenishment and sand mining. The bounds of sediment movement are x_m (the landward limit of sediment transport affecting the shoreline), and x_o (the seaward limit of sediment movement that affects the position of the shoreline, taken at the base of the shoreface).

If we assume $k \leq 1$, i.e., that sediment eroded as the shoreface retreats is not all sand-sized or larger, the solution of Equation 4 is

FIGURE 2

DEFINITION SKETCH, EVERTS' (1984) METHOD



$$k \left\{ \int_{x_c}^{x'_c} f(x)dx - \int_{x_c}^{x'_c} [f(x-s) + a]\, dx \right\} + V_o -$$

$$\left\{ \int_{x_e+s}^{x_c} [f(x-s) + a]\, dx + \int_{x_m+s}^{x_e+s} h(x)dx - \int_{x_m+s}^{x_c} f(x)dx + \int_{x_o+s}^{x_o} j(x)dx \right.$$

$$\left. + \int_{x_c}^{x_o+s} [f(x-s)+a]\, dx - \int_{x'_c}^{x_o} f(x)dx \right\} = 0 \qquad (5)$$

When solved for s, shoreline change is the average for a coastal reach of some specified length. The three unknowns in Equation 5 are s, x_c and x'_c. Because of the site-specific nature of the shape of the initial and later profiles, the variable nature of the value of k, and other site-specific considerations including V_o, and because high-speed computers allow a numerical integration and solution of Eq. 5 by trial and error, it will rarely be desirable to attempt a simplified solution.

The shape of the equilibrium shoreface profile must be considered when the value of k is less than 1; that is, the region of fill must be integrated separately because k is a coefficient applied only to the V_1 region. Sediment deposited in V_g and V'_g is assumed to be of sand size or greater because the depositional surface is on the shoreface or landward of it. Landward transport to the backbeach area by overwash or wind processes typically involves only sand.

Boundaries of integration include the seaward limit of the equilibrium shoreface profile at x_o, the landward limit of the shoreface at x_e, and the landward limit of sediment transport on the backbeach, x_m, all of which are known or can be estimated, and two unknown boundaries, x_c and x'_c, respectively, at the landward and seaward limits of the erosional region, V_1 (Fig. 2). The subsequent (after time Δt) shoreface profile is f(x-s)+a, which is the initial shoreface profile, f(x), translated upward a distance, a, and landward a distance, s; the initial and subsequent backbeach profiles, are, respectively, f(x) and h(x). The subsequent backbeach profile, h(x), is specified either as an engineered profile in a developed area, as illustrated in Figure 2, or as a hypothesized natural profile which retains its shape as it moves landward. Integrations of Equation 5 are made by approximation using the trapezoidal rule

$$A = x[1/2\ (z_z + z_n) + z_2 + z_3 \ldots + z_{n-1}] \qquad (6)$$

in which z_1, z_2 ... z_n are surveyed elevations above an arbitrarily-selected zero datum for a series of equally-spaced parallel chords a distance x apart.

TEMPORAL AND SPATIAL AVERAGES

Changes in shoreline position obtained using the Bruun or Everts methods, because of the fluctuating nature of sea level changes and difficulties inherent in establishing net longshore and cross-shore sediment transport rates, must be the average obtained over time and space. The time average (in Δt) must be such that effects of the net sea level rise are considered. The spatial average is that obtained for a designated alongshore reach in which net sediment transport rates can be estimated over the time period, Δt.

Minimum Time Required

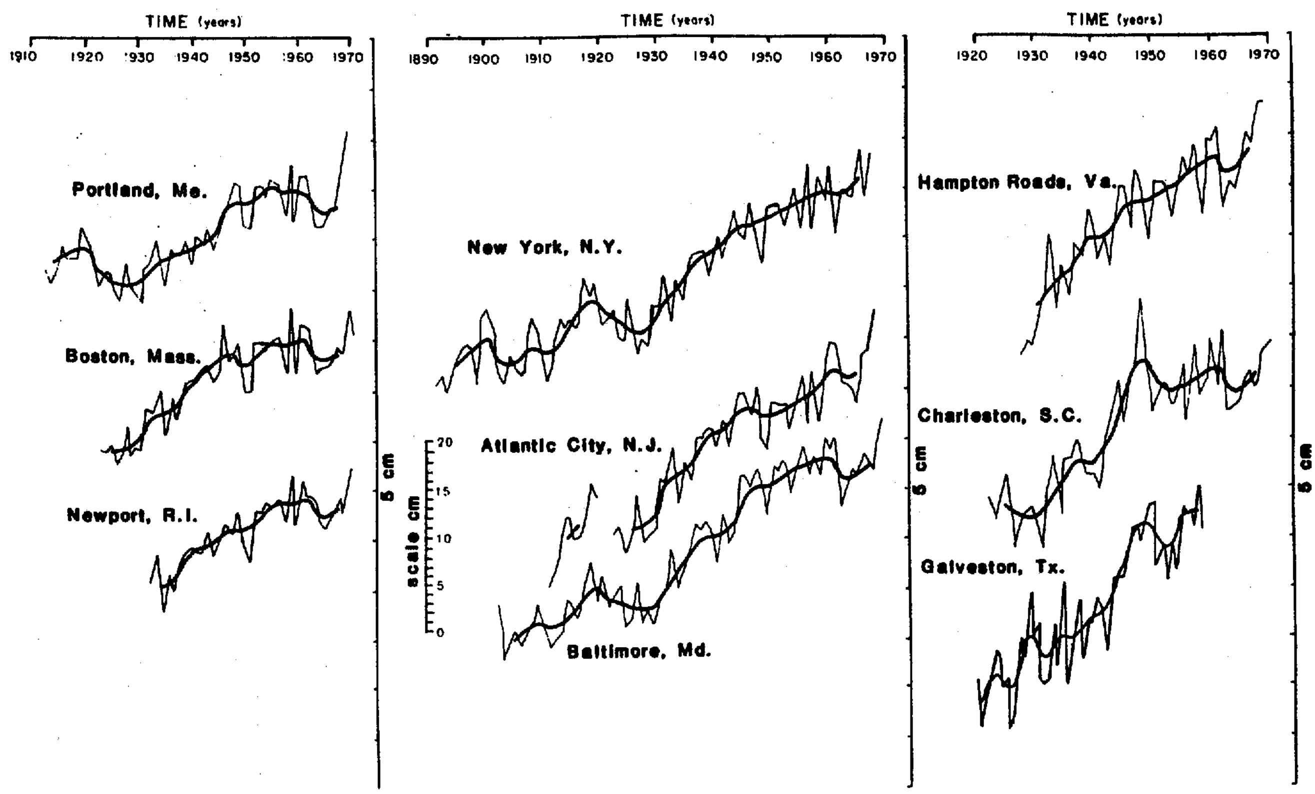
Sea level rise must be considered, and averaged, over a relatively long time period. The magnitude of changes in water surface elevation decreases as the frequency of change decreases (Fig. 3). The entire shoreface profile does not respond by moving vertically upward (and possibly landward) from its base to the shoreline, as the water surface fluctuates at the frequency of the tides, a lunar month, or even a few years. Dynamic shoreface equilibrium is maintained as the shoreface is "swept" to its base and in an alongshore direction with sand over a long time period. For example, when rates of sea level rise at Atlantic City, New Jersey (Fig. 3), are compared to rates of shoreline change at three New Jersey beaches over the 1963-1972 period (Everts and Czerniak, 1977) no relationship is found between the average sea level change from one year to the next and the average shoreline change between years. The variation in yearly sea surface elevation between years (Fig. 3) is about equal to the net change that occurs over a period of 30 years. In addition, because waves, winds, and currents vary on scales that certainly exceed years, averaged values of alongshore sediment transport and cross-shore sediment transport require averaging at periods in excess of a few years. The location of nodal "points" in alongshore transport also varies from year to year depending on wave climate.

Everts (1984) showed that the shoreface at Smith Island, Virginia, about 90 km south of Ocean City, probably maintained a dynamic equilibrium shape as sea level rose 0.0022 m/yr (0.007 ft/yr) over time intervals of about 70 years (survey frequency) during a 130-year period when the shoreline retreated 700 m (2350 ft). Therefore, at a location where the shoreline retreat rate is at least five times as great as that at Ocean City, the dynamic equilibrium assumption appears applicable when shoreline retreat and sea level rise was averaged for 70 years. At an interval of 30 years, it appeared the shoreface shape varied from its longer-term average at Smith Island.

Because relatively good sea level data are available near Ocean City starting about 1930 and extending to the present, and because shoreline change data and surveyed profiles cover the same period, it seems reasonable to select a shoreline average for 50 years (1930-1980) at Ocean City for this investigation.

FIGURE 3

RECENT SEA LEVEL CHANGES ALONG THE U.S. COAST, BASED ON TIDAL GAUGE DATA (from Hicks 1978)



Alongshore Bounds

To obtain as accurate a long-term average of the net gain or loss of sand to the system as possible, it is necessary to select alongshore bounds on the control volume where longshore sediment transport rates are known or can be estimated over the period selected (50 years). In the study area these alongshore boundaries are best located at Indian River Inlet (north boundary) and Ocean City Inlet (south boundary). Sediment transport is out of the study reach at both locations. The location of the divergent nodal reach is thought to be between the villages of Fenwick Island and Bethany Beach.

DATA REQUIREMENTS

Table 1 contains the data required to solve Equations 1, 2, 3, and 5. These data are an average for the 31,190-m long (19.4-mi long) shoreline reach between Indian river Inlet and Ocean City Inlet for the 50-year period between 1930 and 1980. Most of the data elements are presented separately in the following sections. All data were obtained from published and unpublished sources; fieldwork was not a part of this investigation.

Profile Shape

Shoreface profile shape is a variable in Equation 5 when $k \leq 1.0$, which it is along the study reach. The average shoreface profile was obtained by averaging, with equal weight and by eye, all the Ocean City profiles for 1979 (Fig. 4). These profiles were obtained by Corps of Engineers surveyors from the Baltimore District (U.S. Army Corps of Engineers, 1980). A nearly-the-same average profile was obtained independently by another person (Coyne Foster, Technical Aide, Moffatt & Nichol, Engineers). His profile for 1979 was within ±1-ft vertical of that given in Figure 4. A similar weighted, average profile was obtained from 1964 Corps of Engineers-Philadelphia District profiles and also independently duplicated for the coastal reach of Delaware from the Maryland border to Indian River Inlet. Depth-distance pairs obtained from that profile were similar to those of the average 1979 Ocean City profile. The 1979 average Ocean City profile is used in the Bruun and Everts analyses.

Both Leatherman (Chapter 2, this report), who supplied the Ocean City Profiles, and J. Gebert of the Philadelphia District, Corps of Engineers, who supplied the Delaware profiles, noted that shoreface appeared to be steepening when profiles of different years were compared. Because of the concern that the shoreface was steepening, which would negate the dynamic equilibrium shoreface assumption inherent in using Equation 5, a comparison of profiles was made to determine whether that assumption was valid for this coastal reach. All Ocean City profiles for the years 1929, 1965, 1978 and 1979, and Delaware profiles for 1954 and 1964 were averaged as previously discussed. The Ocean City profiles are shown in Figure 4. A later set of profiles is available for Delaware, but was not included in the analysis because it was provided at a different scale, and time/cost considerations prohibited its use. The following conclusions were drawn from comparisons of the average profiles from different survey years:

TABLE 1. VALUES USED IN CALCULATIONS

1. Time Interval: 50 years (1930-1980)

2. Alongshore Boundaries: south jetty, Indian River Inlet, to north jetty, Ocean City Inlet (about 31,190 m or 102,300 ft)

3. Base of Shoreface: a) depth below MSL*: z_o = -8.5 m (-28 ft)

   b) distance from MSL shoreline: ℓ (Fig. 1) = x_o (Fig. 2) = 700 m (2200 ft)

4. Crest of Foredune: $z_e = z_m$ = +4 m (13 ft) above MSL

5. Vertical Profile Dimension: h (Fig. 1) = 12.5 m (41 ft)

6. Relative Sea Level Rise: a = 0.0036 m/yr (0.0118 ft/yr)

7. Portion of Sand Landward of Shoreface: k = 0.75

8. Net loss in Sand Volume in Control Volume: $V_o = 10.6 \times 10^6\ m^3$ ($14.0 \times 10^6\ yd^3$)

   a. Longshore Losses: $V_\ell = 10.2 \times 10^6\ m^3$ ($13.4 \times 10^6\ yd^3$)

   b. Losses at Base of Shoreface: $V_a = 1.05 \times 10^6\ m^3$ ($1.4 \times 10^6\ m^3$)

   c. Losses Resulting From Overwash Transport:

   $$V_w = 0.37 \times 10^6\ m^3\ (0.48 \times 10^6\ yd^3)$$

   d. Losses Resulting from Aeolian Transport: $V_a = 0$

   e. Losses Through Non-Bounding Inlets: $V_i = 0$

   f. Losses from Sand Mining: $V_m = 0$

   g. Gains from Beach Replenishment: V_f $10^6\ m^3$ ($1.4 \times 10^6\ yd^3$)

9. Average Shoreline Change: s = -53.5 m (-176 ft)

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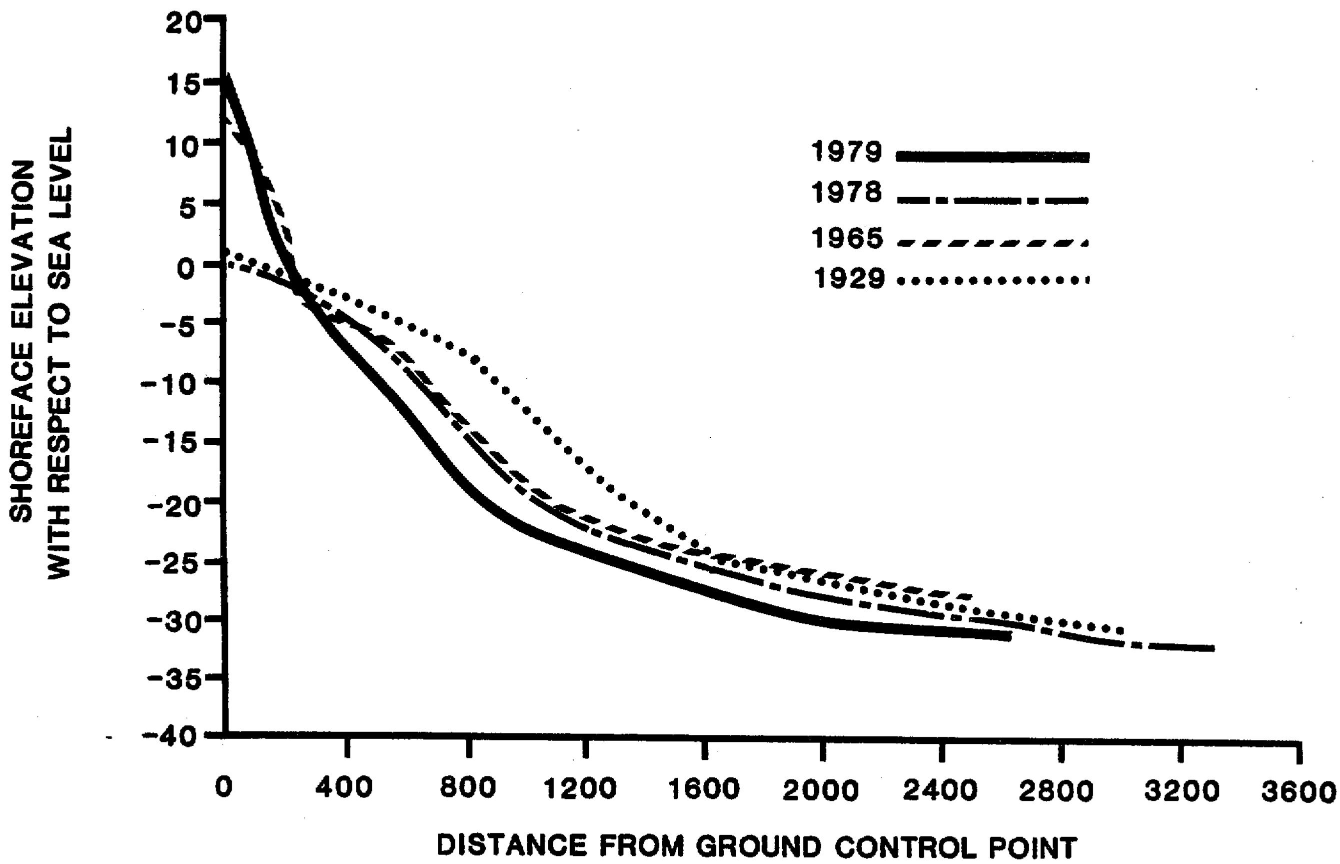
* MSL = mean sea level.

FIGURE 4

AVERAGE SHOREFACE PROFILES FOR THE SURVEY YEARS 1929, 1965, 1978 and 1979
Obtained by Averaging All Profiles Available for a Given Year Along the Ocean City, Maryland, Coast
(Ocean City inlet to Maryland/Delaware state line)



(1) Because profiles from both north and south of the states line were observed to "steepen," and because those profiles were obtained independently, the apparent steepening (explained below) is considered to have occurred and to not be an artifact of the survey programs.

(2) All profiles at each reach superimpose very well when they are shifted in a horizontal direction, except near the MSL shoreline. For example, the 1929 Ocean City profile, when shifted about 220 ft landward, lies atop the 1965 and 1978 Ocean City profiles from the base of the shoreface to a depth of -7 ft (MSL). Above -7 ft, the more recent profiles steepen.

(3) It is difficult to explain the large horizontal distance between the 1978 and 1979 profiles. While the 1979 profile is up to several feet lower (vertical distance) and landward (horizontal distance) than the 1978 profile, when shape is compared by moving the 1978 profile landward, the profiles are found to be similar. An apparent survey problem may exist here.

(4) The lack of landward retreat of the upper part of the profile while the rest of the profile retreated is not explained using the survey data and is not accounted for volumetrically in shoreline change analyses. A possible explanation for the apparent shoreline stability in recent years is: (a) groins constructed at Ocean City have tended to hold the shoreline and uppermost shoreface in a relatively fixed position; (b) sand scraping, in which sand is moved landward from near MSL to create a dune to protect near-beach structures, may also have the short-term effect of keeping sand on the foreshore and behind it, while wave activity and sea level rise continue to move sand and maintain an equilibrium shoreface shape in the nearshore and offshore zone, and (c) beach nourishment in 1961 and 1962 may also have had the effect of maintaining the upper beach. All three situations result in human manipulation of the upper beach while the major portion of the shoreface continues to retreat. The profile shapes shown in Figure 4, using this not-too-conclusive evidence, are considered to remain dynamically constant as the profile retreats.

When the results of this analysis are compared to shoreline retreat rates after 1961, the volume change is accounted for, but the shoreline retreat is not evident because the shoreline was (apparently) artificially held. When long-term changes are considered the methodology should correctly predict sand volume changes. Artificially holding the shoreline without the addition of beachfill from outside the system cannot continue indefinitely. The shoreface cannot continue to retreat (and, in essence, steepen) much longer at Ocean City without shoreline retreat.

Sea Level Rise Rate 1930-1980

The relative sea level rise rate is herein defined as the rate of change (slope) in the yearly mean sea surface elevation for a period of 50 years (1930-1980). Sea level changes relative to land at any location are a function of global changes in the volume (sea surface contraction and expansion and changes in the geometry of the ocean basins) and mass (polar ice contributions and withdrawals) of the oceans. On a regional scale the sea surface may also rise or fall over a relatively long period as the local freshwater contribution varies and regional climatic conditions vary, i.e., atmospheric pressure, wind-shear stress on the sea surface, and temperature. In addition, the land may rise or fall relative to the sea surface by tectonic deformations, compaction, and other factors. Holdahl and Morrison (1974) show the rate of elevation change (land subsidence) at Lewes, Delaware, to be about 3 mm/yr and 2.4 mm/yr at Hampton Roads, Virginia, between 1920 and 1942 and 1970 and 1971. An analysis of tidal gauge records indicates that the total relative rate of sea level rise, a, was 0.012 ft/yr (0.0036 m/yr) when differential subsidence is considered near Ocean City.

Sediment Size Distribution Landward of Shoreface

The Maryland Geological Survey and Professor J. Kraft of the University of Delaware have obtained borings of the region behind the shoreface.

The sand and the silt/clay regions of Figure 5 were integrated above the base of the shoreface (-8.5 m, or -28 ft, MSL) to determine the portion of sand behind the shoreface. This information was supplemented by boring data collected and described by others. Based on an examination of well borings, Rasmussen and Slaughter (1955) identified the Pleistocene deposits landward of the Ocean City shoreface as mud, sand, and "marsh" material, with mud usually the dominant constituent. Near the Maryland-Delaware line, Weigle and Achmad (1982) showed the shoreface was backed by sand with minor clay amounts. The portion of sand in the sand zone of Figure 5 was assumed to be 1.0 of the total sediment (100%). The sand portion of the silt-clay zone of Figure 5 was assumed to be 0.1. Figure 6 shows the estimate of the total portion of sand, by depth, behind the Ocean City shoreface. The total portion of sand behind this shoreface (above -8.5 m, MSL) is k = 0.75. This value is an approximation and could be a significant source of error in the shoreline change test (but will not be a problem in calculating beach nourishment requirements because k = 1.0).

Perlin et al. (1983) reference Kraft's work which shows that the portion of sand behind the Delaware shoreface may be slightly lower than that behind the Ocean City shoreface. Kraft describes the Pleistocene Headlands, which tend in a northeasterly direction and crop out on the shoreface at Bethany Beach and North Bethany Beach, as composed of mud, and mud and sand. He also notes there is a maximum 20 cm (0.7 ft) of sand on the lower and middle shoreface in this region. This is the "active" surface on the retreating shoreface. The "active" zone is indicative of the retreat of the shoreface. Because more substantive information on sand composition is unavailable, the portion of sand behind the Delaware shoreface is taken to be the same as that farther south, i.e., k = 0.75.

FIGURE 5

SEDIMENT SIZE BENEATH THE BARRIER ISLAND AND LANDWARD OF THE SHOREFACE--AT OCEAN CITY, MARYLAND

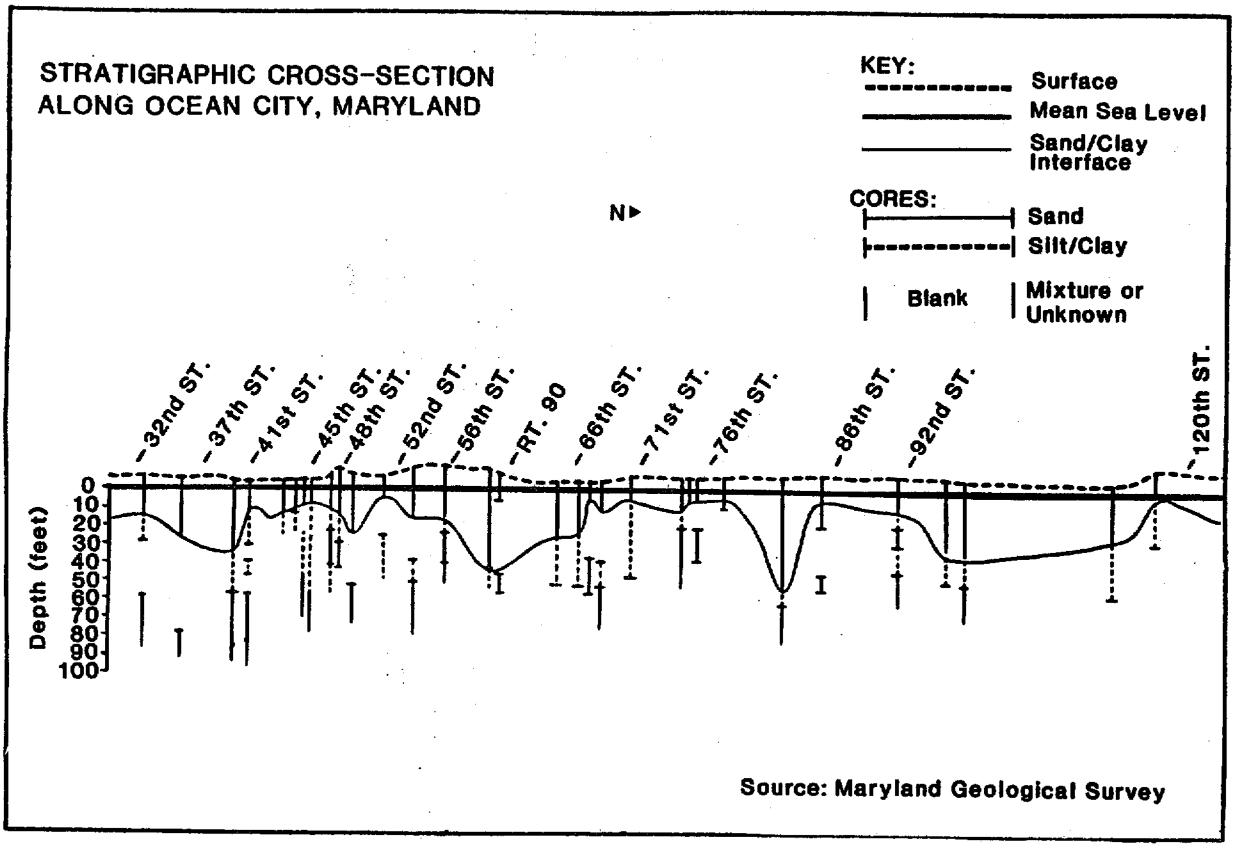
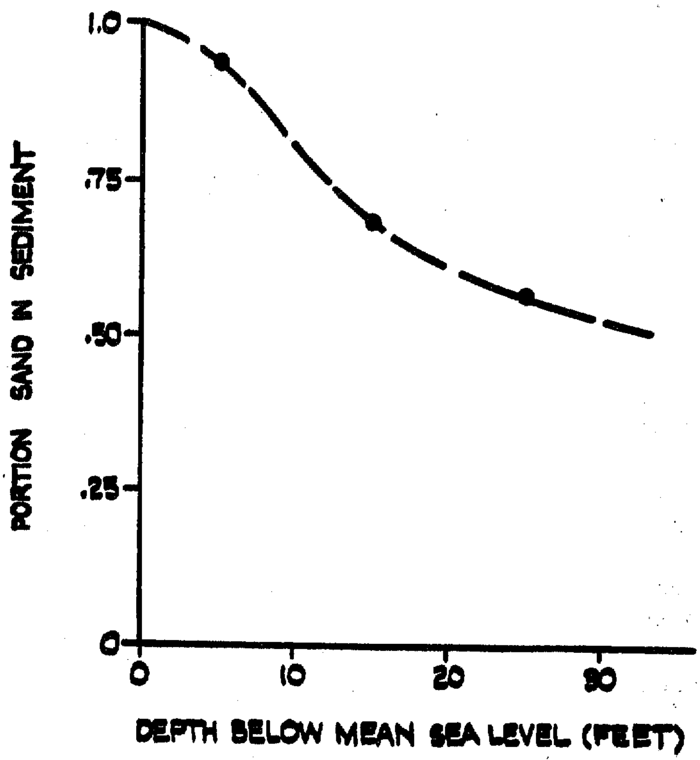


FIGURE 6

PORTION OF SAND BEHIND THE SHOREFACE AND ABOVE -8.5 m (-28 ft) MEAN SEA LEVEL AT OCEAN CITY, MARYLAND



Net Sand Transport Into and Out of Control Volume

Sand transport rates into and out of the control volume are addressed in this section. The control volume is bounded by the base of the shoreface (about -8.5 m, or -28 ft, MSL) and the crest of the foredune, and in an alongshore direction by Ocean City Inlet and Indian River Inlet. V_o in the time Δt (1930-1980) is

$$V_o = V_n + V_c + V_f + V_m + V_w + V_a + V_i \qquad (7)$$

in which V_n = net sand volume contributed to or lost from the control volume by alongshore sand transport, V_c = net sand volume change as the result of shore-normal transport at the base of the shoreface, V_w = net volume change behind the foredune as a result of overwash transport, V_a = net volume change behind the foredune as a result of aeolean transport, V_i = net volume change landward of the foredune as a result of inlet(s) that opened in the control volume between 1930-1980, V_f = gain as a result of the addition of fill and from outside the control volume, and V_m = loss as a result of sand mining. All values used are given in Table 1.

1. Net Loss By Longshore Transport (V_n). Sand transport in an alongshore direction accounts for the main absolute loss of sand from the control volume. The net longshore sediment transport rates at Ocean City Inlet and Indian River Inlet are available from a number of sources using various lines of evidence.

At Ocean City Inlet, Fulford (personal communication, 1984) said the Corps of Engineers (Baltimore District) assumes a net longshore transport rate since 1933 (inlet opening) of 1.2 x 10^5 m^3/yr, south (1.6 x 10^5 yd^3/yr, south). It is reasonable to believe it was also that value prior to inlet opening in 1933. Dean et al. (1978) using impoundment volumes from north of the inlet, a sediment budget for the inlet area, and the growth rate of the ebb-tidal shoal, concluded the net longshore transport rate is probably 0.38 x 10^5 to 1.14 x 10^5 m^3/yr, south (0.5 to 1.5 x 10^5 yd^3/yr, south). Everts (1983) in a discussion of shoreline changes south of the inlet concluded that the rate 14.8 km south of an assumed nodal location at South Bethany Beach was 1.2 x 10^5 m^3/yr (1.6 x 10^5 yd^3/yr), but that volume probably includes some material that moved north into the inlet. Based on no more than an arbitrary selection--near the average of the above estimates--the average net longshore transport rate at Ocean City Inlet is taken as 1.2 x 10^5 m^3/yr, south (1.6 x 10^5 yd^3/yr, south) or 6 x 10^6 m^3 (7.9 x 10^6 yd^3) between 1930 and 1980.

At Indian River Inlet, Perlin et al. (1983) estimated that the ebb-tidal shoal is accumulating sand at 0.66 x 10^5 m^3/yr (0.87 x 10^5 yd^3/yr); the flood-tidal shoal is in equilibrium with the 18-yr average dredging of 0.57 x 10^5 m^3/yr (0.75 x 10^5 yd^3/yr); and the net longshore transport at the inlet is 1.21 x 10^5 m^3/yr, north (1.6 x 10^5 yd^3/yr, north). This volume is higher than the 0.84 x 10^5 m^3/yr, north (1.1 x 10^5 yd^3/yr, north) that the Philadelphia District (Gebert, personal communication, 1984) estimates is required to stabilize the beaches north of the inlet. The dynamic nodal position is probably near South Bethany Beach, which is closer to Indian River Inlet than to Ocean City Inlet, and if an equal increase both north and south of the node is assumed, the net longshore sediment transport rate at Indian River Inlet would be less than that at Ocean City Inlet. Accordingly, a net longshore transport rate of 0.84×10^5 m^3/yr, north (1.1×10^5 yd^3/yr, north) or 4.2×10^5 m^3 (5.5×10^6 yd^3) between 1930 and 1980 is used in this investigation.

2. <u>Net Loss at Base of Shoreface</u>. No information exists on net sand transport across the base of the shoreface. Perlin et al. (1983) show the Continental Shelf seaward of the shoreface is surfaced partially by Pleistocene deposits that could not have come from the shoreface, suggesting negligible transport or possibly onshore transport in those areas (patches).

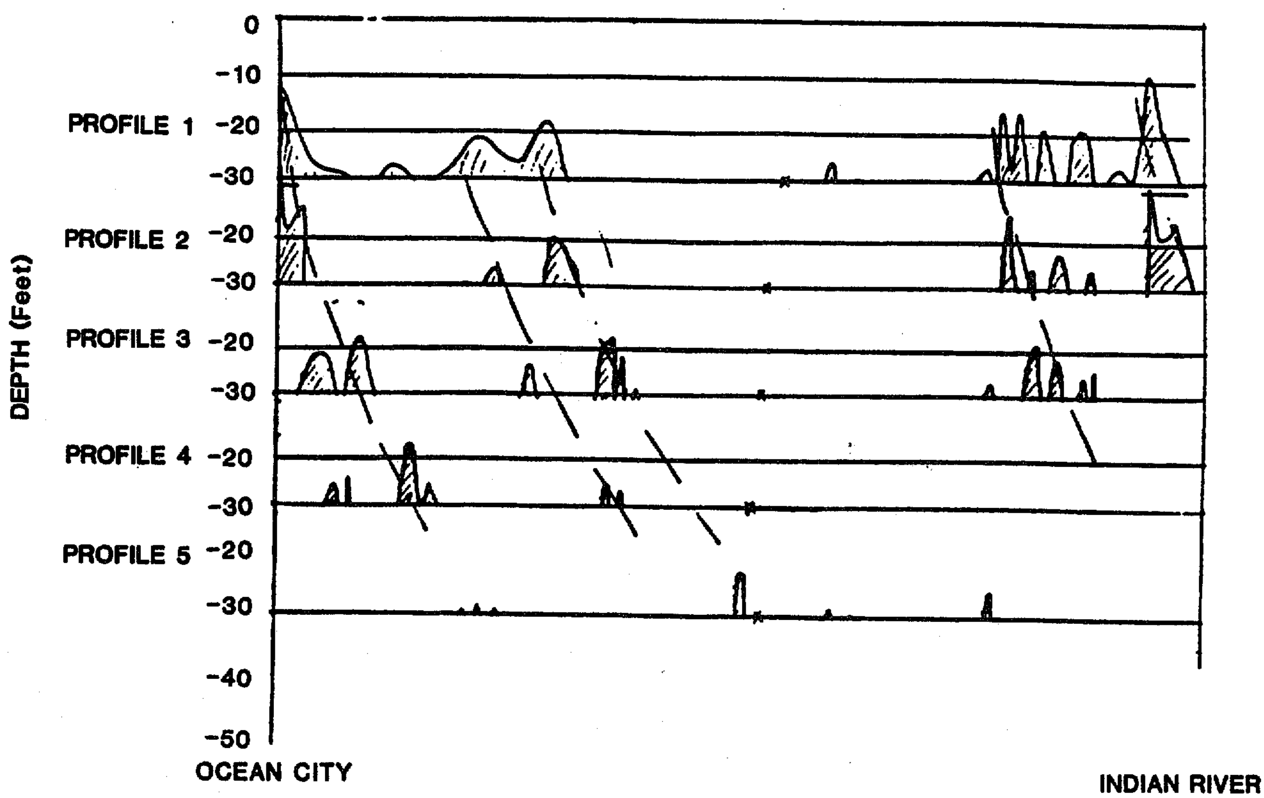
Bathymetry of other regions on the shoreface and inner-Continental Shelf, however, is dominated by shoals which trend north-northeast. Some of these shoals are connected to the shoreface and others, still in line with those at the shoreface, lie isolated on the Shelf surface. The shoals are composed of sand which may have come from the shoreface. Along the ocean coast of North Carolina and Virginia, Everts et al. (1983) found that similar shore-connected ridges significantly influenced the shoreline. The shoreline north of the intersection of predominant ridges with the shoreface retreated at an accelerated rate compared to the average for the entire shore reach; shorelines south of the ridge intersections prograded or retreated at a lesser rate than the average for the reach. Generally, the major ridge/shoreface intersections (ridges which extended far out onto the inner-Continental Shelf) were located about 5 km south of gentle, convex-outward shorelines, such as that at Ocean City Inlet.

The only sand that moves across the base of the shoreface in the study area is assumed to be sand lost to the shoreface-connected ridges. To obtain the volume lost to those features, five shore-parallel profiles were drawn between the inlets at 700 m (2250 ft), 1050 m (3450 ft), 1550 m (5100 ft), 2500 m (8200 ft), and 3475 m (11,400 ft) from the shoreline. The extension of the shore-connected ridges above the -8.5 m (-28 ft) basal depth of the shoreface is shown in Figure 7. Note the trend of the ridges to the northeast as the distance from shore increases. The shaded area of the ridges at the base of the shoreface (Profile 1, Fig. 7) was found to be 7.9 percent of the total vertical shoreface area. When the volume of sand assumed naturally lost from the shoreface to nourish the ridges is calculated as this percentage of the total shoreface depth (-8.5 m; -28 ft) times length (31,190 mi; 102,300 ft) times retreat rate (about 1 m/yr, or -3.4 ft/yr as developed later), the net yearly loss is 21,000 m^3/yr (27,500 yd^3/yr) or 10^6 m^3 (1.4×10^6 yd^3) between 1930 and 1980. This is about one-tenth the volume lost by longshore transport out of the system.

3. <u>Net Loss by Overwash Transport</u>. The only storm in which large quantities of sand were moved landward of the foredune occurred on 7 March 1962. The volume moved is unknown, and most of the sand was subsequently returned to the beach in developed areas. In undeveloped areas, much of the overwash deposit was also probably naturally returned by aeolian processes as Leatherman found occurred on Assateague Island. Assuming that a washover deposit 300-m deep (1000 ft) and 0.3-m thick (1 ft) formed along 40 percent of

FIGURE 7

SHORE-PARALLEL PROFILES OF SHORE-CONNECTED RIDGES ABOVE THE ELEVATION OF THE BASE OF THE SHOREFACE (-8.5 m, -28 ft, MSL) BETWEEN OCEAN CITY INLET AND INDIAN RIVER INLET



the shoreline during the 1962 storm, about 1.1 x 10^6 m^3 of sand would have moved away from the beach. Next, assuming two-thirds of that sand was naturally or artificially returned to the beach, 3.7 x 10^5 m^3 (4.9 x 10^5 yd^3) would have been "permanently" lost from the control volume.

4. Net Changes Due to Aeolian Transport. Wind-transported sand losses or gains are assumed to be negligible.

5. Losses Through Non-Bounding Inlets. Between 1930 and 1980 no new inlets were opened in the control volume so no losses occurred by this mechanism.

6. Losses by Sand Mining. Apparently the only artificial transport of sand on the beaches was "sand scraping" that occurred in the 1970's and 1980's. This moved sand from the lower foreshore to create or improve the foredune. There was no net loss to the control volume.

7. Gains from Beach Replenishment. Gains from this source were 0.87 x 10^6 m^3 (1.15 x 10^6 yd^3) from the sound to Ocean City beaches in 1962 and 7.6 x 10^4 m^3 (10^5 yd^3) to Bethany Beach in 1961 and 5 x 10^4 m^3 (7 x 10^4 yd^3) to Bethany Beach in 1962 and 5 x 10^4 m^3 (7 x 10^4 yd^3) to South Bethany Beach in 1962. The total quantity of sand from outside sources that entered the control volume between 1930 and 1980 appears to be 10^6 m^3 (1.4 x 10^6 yd^3), all of which was placed after 1960.

Shoreline Changes (1930-1980)

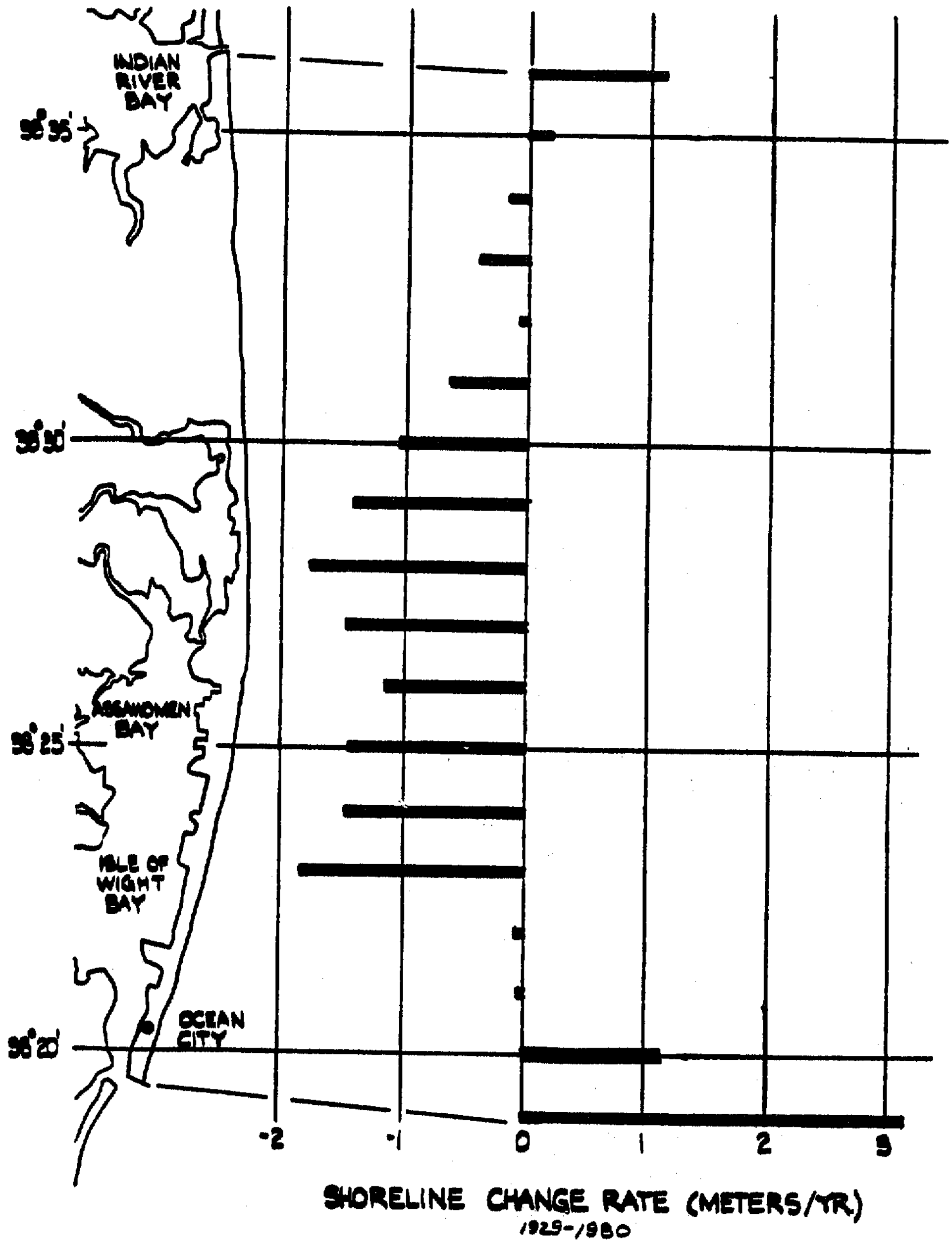
Shoreline change maps constructed by the National Ocean Services (NOAA) were used to obtain the average shoreline change rate for the reach between the inlets and over the 51-yr time period 1929 to 1980 (Fig. 8). This rate was calculated using 101 equally spaced measurement transects (6 per minute of latitude on the NOAA maps). The average rate was -0.644 m/yr (-2.1 ft/yr). The rate north and south of the Maryland-Delaware state's line was similar (-0.60 m/yr, south reach; -0.68 m/yr, north reach). Leatherman (Chapter 2) calculated an average rate of -0.58 m/yr (-1.9 ft/yr) for the 1850-1980 period for the Ocean City reach. In an Environmental Impact Statement, the Corps of Engineers (1980) stated the historic retreat rate was -0.8 m/yr (-2.3 ft/yr).

Strikingly, the shoreline change rate using the NOAA maps for the period 1961/62 to 1980 was -0.19 m/yr (-0.6 ft/yr) south of the states line and +0.28 m/yr (+0.9 ft/yr) north of the states line. The average for the entire reach in the 1961/62 to 1980 period was a progradation of +0.08 m/yr (+0.25 ft/yr). This occurred during a period when sea level rose relative to land at all nearby sites and when the shore of Assateague Island south of Ocean City Inlet retreated at a rate equal to the rate it had retreated since the inlet jetties were constructed in 1933. The 1961/62-1980 period is a time when the shoreline, as observed by comparing profiles (Fig. 4), was held in place, but the rest of the shoreface retreated.

Shoreline changes after 1961 do not reflect the general retreat of the shoreface (Fig. 4) but are controlled by: (1) groin construction at Ocean City and Bethany Beach, (2) beach replenishment in the early 1960's which

FIGURE 8

SHORELINE CHANGE RATES FOR THE PERIOD 1929-1980
(from NOAA Shoreline change maps, used with permission)
The 1961-1980 average rate is +0.08 m/yr while
the shown 1929-1980 rate is -1.05 m/yr.



built up the beach and very shallow portions of the shoreface and was subsequently held by the groins, and (3) sand scraping (movement of sand from the foreshore to create an artificial foredune farther landward). All contributed to holding the uppermost part of the shoreface while the lower shoreface retreated. The shoreline retreat rate, if the shore was not modified in these ways, would be greater than -0.64 m/yr (-2.1 ft/yr). The retreat between 1929 and 1980 (average = -32.8 m) shown on the NOAA maps occurred between 1929 and 1961/62 (which was measured on the maps), and if we assume the pre-1961/62 retreat rate would have continued to the present if the upper shoreface had not been "stabilized," the actual retreat rate would be -1.05 m/yr (-3.4 ft/yr).

CALCULATIONS

Past Shoreline Changes

Calculations using Bruun's (1962, 1983) method and Everts' (1984) method with data from Table 1, are given in Table 2. The effect of sea level rise produced 19 percent of the shoreline retreat (Everts' method) that would have occurred without human intervention at Ocean City between 1930 and 1980. Sand volume losses from the system accounted for 81 percent of the calculated retreat. If the shoreface had been backed with sediment composed entirely of sand (k = 1.0), the calculated shore retreat would have been 19 percent less. Bruun's (1962, 1983) methods result in a substantial underprediction of the shore-retreat rate. Everts' (1984) method predicts a rate that is slightly higher.

Future Shoreline Changes

A two-step approach was used to provide the requested future shoreline change rates and beachfill requirements. Using Everts' (1984) method, the average calculated shoreline change rate (-1.12 m/yr or -3.7 ft/yr) was checked against the measured rate (-1.03 m/yr or -3.4 ft/yr). The input data were then adjusted so the past calculated rate was equal to the measured rate. This adjustment was then made in the independent variable most likely to have been incorrectly determined. Figure 9 shows the variation in shoreline change rates as the rate of sea level rise (a) the rate at which net sand volume increases or decreases (V_o), and the portion of land behind shoreface (k) are varied individually as others are kept constant at estimated 1930-1980 values (open circles). The shoreline change value varies greatly with small changes in k, suggesting k may be in error. A k adjustment to k = 0.82 yields a calculated value equal to the "measured" value (-1.03 m/yr). The value of "a" used in the calculation (Table 1) is probably quite good (Fig. 3). Likewise, values of the components of V_o (Table 1) are probably less questionable than the estimated value of k originally used.

Assuming no beachfill (V_f in Table 1 = 0) and no overwash transport losses because of anticipated continuing artificial foredune creation and future development (V_w in Table 1 = 0), and assuming all other components of V_o will remain the same as given in Table 1, the net future loss rate of sand along

TABLE 2. CALCULATED SHORE RETREAT FOR OCEAN CITY, MARYLAND, 1930-1980

Method	Equation	Predicted Shoreline Change, Meters (Feet)	Erosion Caused By Sea Level Rise Percent[1]	Percent of Measured Change[2]
Bruun (1962)	1	10 (33)	100	18
Bruun (1983)	2	12 (39)	100	23
	3	13 (43)	91	24
Everts (1984)[3]	5	56 (184)	19	105
Measured[4]		53.5 (175)		100

[1] Volume change caused by sand transport into and out of control volume, equal to R in Equation 3 and V_o in Equations 4 and 5.

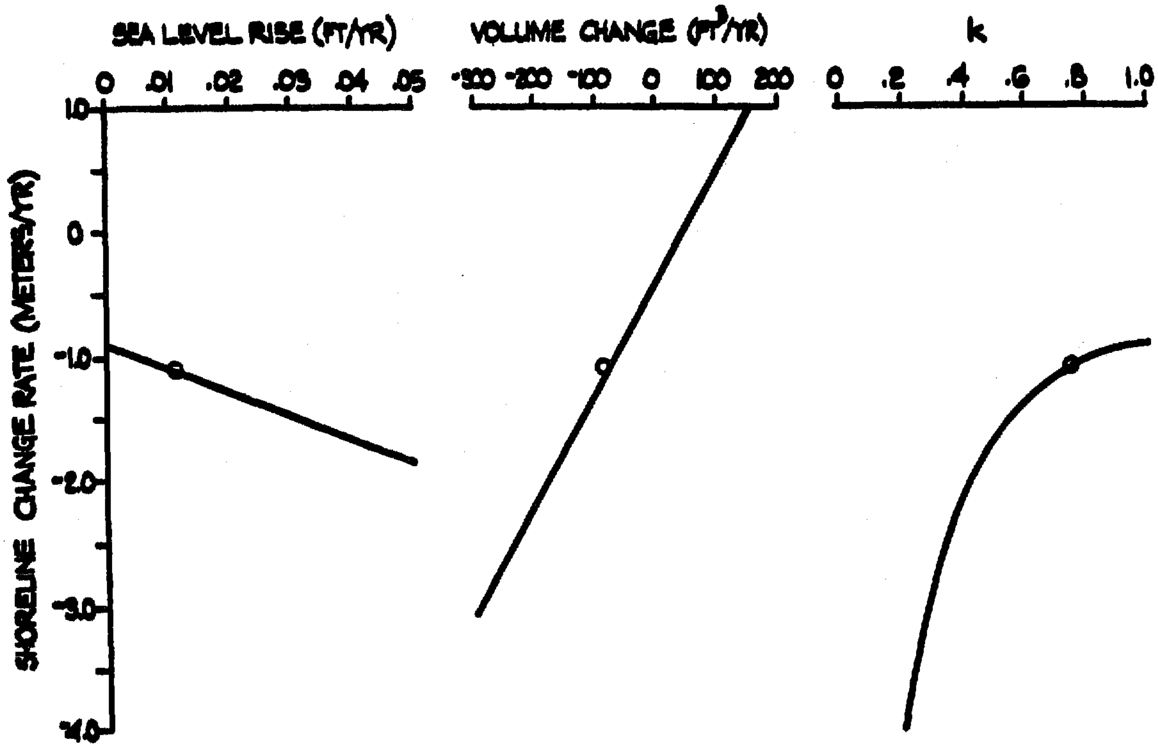
[2] The percent given is the calculated change divided by the measured change times 100.

[3] Shore retreat would have been 19 percent less if eroded shoreface sediment had been all sand.

[4] Shoreline changes between 1961 and 1980 were greatly affected by groin construction, beach nourishment, and possibly sand scraping. While the shoreline was artifically "stabilized," sand volume losses and the effect of sea level probably continued at the 1930-1961 rate during this period. This is an important consideration because a shoreline change rate based on sand volume changes is the essence of the Bruun (1983) and Everts (1984) methods. The -32.7 m (-107 ft) obtained from shoreline change maps for 1930-1961 is assumed, for comparison purposes, to have continued in 1980. Ocean City is not an ideal location to test and evaluate predictive methods because of the large influence of man on the shoreline since about 1961.

FIGURE 9

VARIATIONS IN SHORELINE CHANGE RATE
(Calculated Using Eq. 5)
WITH SEA LEVEL RISE, NET VOLUME CHANGE IN
CONTROL VOLUME, AND PERCENT SAND IN
SEDIMENTS BEHIND SHOREFACE
Open Circles Reference Data Used in 1930-1980 Analyses



the Ocean City reach, V_o, will be taken as -263,000 m^3/yr (-347,000 yd^3/yr) or -2.6 m^3/m-yr (-3.4 yd^3/ft-yr).

Table 3 is a list of two sea level-rise scenarios provided by the Environmental Protection Agency (EPA). Table 4 shows the calculated (Eq. 5) cumulative shoreline retreat that is projected for each scenario. These projected shoreline retreats are averages for the entire shoreline reach and do not reflect alongshore variations that would surely occur (and have occurred in the past as shown in Figure 8). Quite likely, the shoreline retreat would be less than that shown in Table 4 because the jetties would continue to (and increasingly) act as headlands. The result would be that a shallow embayment would form in which net alongshore sediment transport losses (Table 1) would decline at the boundary inlets.

Future Beachfill Requirements

If the shoreline is to be held at its 1984 position, beachfill must be added to counter the -8.4 m^3/m-yr or 18,000 yd^3/mi-yr) lost from the Ocean City beach, plus the increasing effective loss produced by a shift in the shoreface as the sea level rise accelerates. The k-value of the fill material is 1.0, so using the V_o at the zero shoreline change rate shown in Figure 9 is too large (by 19 percent in 1980). Using Equation 5, a continuing net loss by longshore and cross-shore transport of -2.6 m^3/m-yr, (-3.4 yd^3/ft-yr), k = 1.0, and the sea level rise scenarios provided by the EPA (Table 3) for Ocean City from the north jetty of Ocean City Inlet north to the Maryland state line (14,220 m, 46,650 ft), the calculated future fill requirements are as given in Table 5. Bruun's (1983) Equation 3 was used with offshore losses equal R = 12,800 yd^3/yr and r = 1.0. Table 6 shows the percent of the required beachfill material that must be added because of the rise in sea level and that which must be added because of longshore and cross-shore sand transport losses. Sand volume losses resulting from sea level rise will usually require that beachfill be added from outside the control volume. Losses by longshore and cross-shore (at base of shoreface) transport may possibly be mitigated using proper structures that slow or halt the transport of sand, thereby reducing the volume of required beachfill.

SUMMARY

The effect on shoreline position of sea level rise and changes in sand volume on the shoreface and barrier island of Ocean City, Maryland, are addressed in this paper. Results are given in a series of Tables and in Figure 10. Table 1 shows the data used in calculating shoreline change for the period 1930-1980. Table 2 provides a comparison of the Bruun (1962, 1983) and Everts prediction of shoreline retreat for that period to the measured retreat. EPA-provided sea level rise scenarios given in Table 3, are used to forecast the shoreline changes to 2075 illustrated in Table 4. Table 5 shows projected beachfill requirements to 2075 using the Table 5 sea level rise scenarios, and Table 6 shows the percent of the total beachfill requirement that can be attributed to sea level rise.

TABLE 3. RELATIVE SEA LEVEL RISE SCENARIOS[1]

1. ABSOLUTE RISE OVER 1980 LEVEL (Centimeters [feet])

Year	Current Trend	Mid-Range Low Rise	Mid-Range High Rise
2000[2]	7 (0.24)	12.4 (0.41)	16.8 (0.55)
2025[2]	16 (0.53)	34.3 (1.12)	47.4 (1.55)
2050[2]	25 (0.83)	65.2 (2.14)	91.5 (3.00)
2075[2]	34 (1.13)	108.3 (3.55)	153.9 (5.05)

2. RATE OF SEA-LEVEL RISE (Centimeters/year [feet/year])

	Mid-Range Low	Mid-Range High
1980-2000[2]	0.62 (0.020)	0.84 (0.028)
2000-2025[2]	0.88 (0.029)	1.22 (0.040)
2025-2050[2]	1.24 (0.041)	1.76 (0.058)
2050-2075[2]	1.72 (0.056)	2.50 (0.082)

---

[1] Sea level rose 18 cm between 1930 and 1980 (0.36 cm/yr). Rate obtained using data from nearby tidal gauge records (Hicks, Debaugh, and Hickman 1983) and interpolated using regional crystal deformation data (Holdahl and Morrison, 1974).

[2] EPA estimates (Hoffman, Keyes, and Titus 1983) which illustrate cumulative rise and which include a 1.8 mm/yr local subsidence rate as per Holdahl and Morrison (1974), with 1980 as base year.

TABLE 4. SHORELINE RETREAT SCENARIOS FOR OCEAN CITY, MARYLAND[1]

YEAR	SHORELINE RETREAT RATE (feet/year)					
	CURRENT TREND		MID-RANGE LOW RISE		MID-RANGE HIGH RISE	
	Everts Eq. 5	Bruun Eq. 3	Everts Eq. 5	Bruun Eq. 3	Everts Eq. 5	Bruun Eq. 3
1980-2000	3.4	0.81	4.2	1.10	4.8	1.9
2000-2025	3.4	0.81	6.2	1.98	7.1	2.7
2025-2050	3.4	0.81	7.8	2.74	9.5	4.0
2050-2075	3.4	0.81	10.9	3.83	14.7	5.6

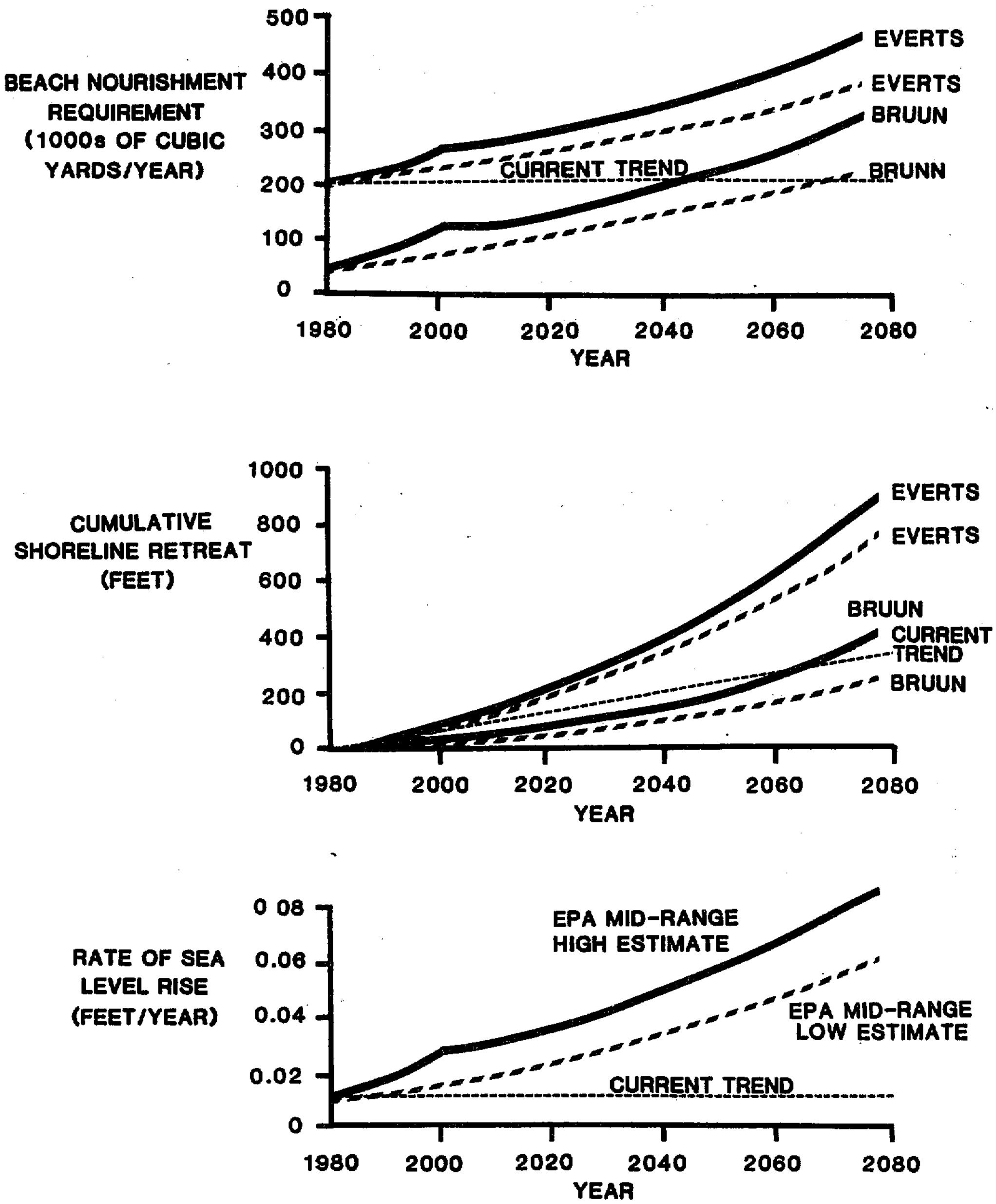
YEAR	CUMULATIVE SHORELINE RETREAT (feet)					
	CURRENT TREND		MID-RANGE LOW RISE		MID-RANGE HIGH RISE	
	Everts Eq. 5	Bruun Eq. 3	Everts Eq. 5	Bruun Eq. 3	Everts Eq. 5	Bruun Eq. 3
1980	0	0	0	0	0	0
2000	68	16	84	22	95	38
2025	153	36	238	72	273	106
2050	238	57	434	140	511	206
2075	323	77	707	236	878	346

---

[1] Using EPA sea level rise scenarios (Table 3); assumes no shoreline manipulation or "hardening" such as has occurred since about 1960, no beach nourishment, and no overwash losses.

FIGURE 10

ESTIMATED FUTURE SHORELINE RETREAT AND BEACH NOURISHMENT REQUIREMENTS AT OCEAN CITY, MARYLAND, FOR TWO EPA SEA LEVEL RISE SCENARIOS



Line representations for Everts' (1984) and Bruun's (1983) models are given for shoreline retreat and beachfill requirements. The curves are keyed to sea level scenarios at the bottom of the figure.

TABLE 5. CALCULATED BEACHFILL REQUIREMENTS FOR OCEAN CITY, MARYLAND[1]

YEAR	FILL REQUIREMENT (yd^3/yr)					
	CURRENT TREND		MID-RANGE LOW RISE		MID-RANGE HIGH RISE	
	Everts Eq. 5	Bruun Eq. 3	Everts Eq. 5	Bruun Eq. 3	Everts Eq. 5	Bruun Eq. 3
1980-2000	203,000	48,000	230,000	73,600	260,000	119,000
2000-2025	203,000	48,000	270,000	123,000	310,000	165,000
2025-2050	203,000	48,000	310,000	165,000	380,000	233,000
2050-2075	203,000	48,000	370,000	226,000	470,000	324,000

[1] Using EPA sea level rise scenarios (Table 3) and Equation 5; assumes size distribution of fill material is equal to size distribution of native beach sand.

TABLE 6. PERCENT OF BEACHFILL REQUIREMENT ATTRIBUTED TO SEA LEVEL RISE AT OCEAN CITY[1]

YEAR	CURRENT TREND		MID-RANGE LOW RISE		MID-RANGE HIGH RISE	
	Everts Eq. 5	Bruun Eq. 3	Everts Eq. 5	Bruun Eq. 3	Everts Eq. 5	Bruun Eq. 3
1980-2000	22	74	31	83	39	89
2000-2025	22	74	40	90	49	92
2025-2050	22	74	49	92	58	95
2050-2075	22	74	57	94	66	96

[1] Remainder is produced by sand losses from the control volume.

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CHAPTER 4

ESTIMATES OF EROSION AND MITIGATION REQUIREMENTS UNDER VARIOUS SCENARIOS OF SEA LEVEL RISE AND STORM FREQUENCY FOR OCEAN CITY, MARYLAND

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ABSTRACT

A numerical erosion model is applied to representative beach profiles for Ocean City, Maryland, to estimate: 1) the expected erosion impact of severe storms with 10- to 500-year return periods, 2) the potential erosion impact of sea level rise to the year 2075, and 3) the mitigation requirements, that is, volume of beach fill, needed to maintain the current shoreline position based on predicted erosion due to storms and/or sea level rise.

Storm erosion effects are estimated for the range of possible severe storms with peak storm surge levels associated with 10- to 500-year storms and storm durations associated with a typical hurricane, a typical winter storm, and the longest storm on record--the March 1962 storm. Based on a representative beach profile for Ocean City, erosion estimates range from 500 to 1400 ft^3/ft with probable dune recession of 50 to 100 feet and possibly to 140 feet. Estimated erosion values seem reasonable when compared to qualitative descriptions of the March 1962 storm. According to model verification studies using Hurricane Eloise erosion field data, predictions are considered average estimates with probable errors of $\pm$25 percent to account for natural variations found under field conditions.

Interpretation of storm erosion estimates indicates a significant probability for Ocean City dunes to erode quickly and to permit subsequent overwash, storm flooding, and direct wave propagation into developed areas. Mitigation requirements are developed to prevent dune breaching based on the full range of storm conditions of interest. While mitigation requirements vary according to the desired level of storm protection, required beachfill volumes over the 8-mile Ocean City shore front range from 3,500,000 to 5,000,000 yd^3 to provide protection for the 100-year peak storm surge of all possible durations. In this respect the 3,500,000 yd^3 of beachfill proposed by the Corps of Engineers is found to be adequate for typical hurricanes but may not be adequate for longer winter storm durations.

The average long-term erosion trends are estimated for three sea level rise scenarios corresponding to a continuation of the existing trend and two accelerated scenarios as suggested by the Environmental Protection Agency. Hindcasts of erosion due to conditions between 1929 and 1961 provide a confirmation that methods used to estimate erosion due to sea level rise are valid. However, since 1961 the shoreline position has been stabilized and has not eroded as historical trends or predictions would suggest. At the same time, offshore regions have eroded at what appears to be the historical rate. The effect of this is a steepening of the profile as the existing shoreline position is maintained; this is a potentially unstable situation that could lead to accelerated shoreline erosion to regain a more stable, that is, more mildly sloping, profile form.

Under the three future sea level rise scenarios, average erosion rates of 3.3, 4.8, and 5.8 ft/yr are predicted under the assumption that the shoreline will freely respond to a stable position. For comparison, the historical shoreline erosion rate between 1929 and 1961 was 3.4 ft/yr. By the year 2075, shoreline recessions of 315, 460, and 550 feet are predicted for the three sea level rise scenarios. Total mitigation requirements to maintain the existing

shoreline range from 19,000,000 yd^3 to 40,000,000 yd^3 over the 8-mile Ocean City shoreline for the 95-year period. Mitigation requirements to maintain the existing level of storm protection are approximately the same; these quantities should be increased by 3,500,000 to 5,000,000 yd^3 to provide the additional storm protection for the 100-year design storm.

INTRODUCTION

Shoreline retreat and dune erosion magnitudes and probabilities are estimated for Ocean City, Maryland, based on existing and estimated future conditions regarding sea level rise and storm frequencies. These estimates are intended to complement similar efforts, by other authors, to estimate the erosion impacts of projected sea level rise scenarios to the year 2075. The primary goal of this study, however, is to apply the Kriebel and Dean (1984, 1985) numerical storm erosion model to estimate the short-term erosion potential of severe storms, and to estimate whether storm effects may necessitate more direct and immediate erosion mitigation than the sea level rise induced erosion. The numerical erosion model is then applied to estimate the erosion potential of sea level rise scenarios. The final results indicate the relative severity of the two erosion forcing scenarios, that is, sea level rise versus severe storms, and indicate appropriate mitigation requirements to maintain existing shoreline positions and current levels of storm protection.

Since the major goal of this study is to estimate the erosion potential of severe storms, considerable effort has been made to thoroughly develop, calibrate, and verify the numerical erosion model. Much of this report provides documentation of this verification procedure, which is considered essential if the most realistic and reliable estimates of the storm erosion potential are to be obtained. In Section I, modifications of the numerical erosion model are described; specifically, methods are included for estimating beach slope changes and dune steepening during erosion. In Section II, the modified erosion model is calibrated using Saville's (1957) prototype-scale wave flume experiments. In Section III, a separate calibration is carried out using a reference profile from the Hurricane Eloise data set of pre- and post-storm beach profiles. This section also includes the independent simulation of dune erosion on an additional 20 profiles from the Hurricane Eloise data set, which provides a verification of the model and an estimate of the confidence obtained from model predictions.

In Section IV, the erosion model is applied to estimate the effects of severe storms on the existing Ocean City beach profile forms. The 10-, 40-, 100-, and 500-year return period storms are investigated explicitly from which the effects of other storms may be interpolated. Since storm duration is an important component in determining the storm erosion potential, results are given for three storm durations, corresponding to a typical hurricane, a typical northeast storm, and the longest storm duration expected, that is, that associated with the March 1962 storm. Mitigation requirements for storm protection are also developed in Section IV. In Section V, the erosion model is applied to estimate the erosion potential of three sea level rise scenarios, including net sand volume losses due to longshore sediment transport. Finally, results are summarized to identify mitigation requirements for long-term profile adjustment to sea level rise and net sand volume losses outside of the active profile. Section VI presents a study summary with final conclusions.

SECTION I

DESCRIPTION OF BEACH-DUNE EROSION MODEL

Background

The numerical model for predicting beach and dune profile response to severe storms is based on a theory for equilibrium beach profile development presented by Dean (1977, 1984). Dean analyzed several mechanisms for the formation of dynamic equilibrium beach profile forms and concluded that observed equilibrium profile forms are consistent with the uniform dissipation of wave energy per unit volume in the surf zone. Based on this argument, theoretical profile forms may be found to be described by a monotonic curve as:

$$h = Ax^{2/3} \tag{1}$$

where h is the water depth at some distance x seaward of the shoreline (x=0) and A is a scaling parameter governing the steepness of the profile as in Figure 1. The A parameter is also related theoretically to a unique value of the wave energy dissipation per unit volume, D_*, which exists at all points in the profile when the system is in equilibrium. Based on a least-squares analysis, Dean (1977) determined best-fit A (or D_*) values for 502 beach profiles from the U.S. Atlantic and Gulf coasts. Hughes (1978) and Moore (1982) have analyzed several hundred additional beach profiles; from these sources equilibrium A and D_* values may be empirically related to mean sediment size and sediment fall velocity as shown in Figure 2.

For numerical simulation of beach profile response, it is assumed that a given beach profile will always respond toward its most stable or equilibrium form relative to given water level or wave height conditions. During a severe storm, the increased water level permits storm waves to break closer to shore at first, therefore reducing the width of the surf zone and increasing the energy dissipation per unit volume at all points in the surf zone as depicted in Figure 1. The profile is then "out of equilibrium" since energy dissipation per unit volume is now greater than the equilibrium value D_* throughout the surf zone. Based on the assumption that the profile will evolve toward an equilibrium, i.e., $h = Ax^{2/3}$, shape relative to the new water level and wave height, the net result must be a widening of the surf zone until the actual energy dissipation per unit volume is reduced to D_*. This can only be achieved by a net redistribution of sand over time, with erosion of the beach/dune face and deposition pushing the breakpoint farther off shore.

Based on these concepts, the net offshore sediment flux, Q, is approximated according to the excess energy dissipation per unit volume at each point in the surf zone as:

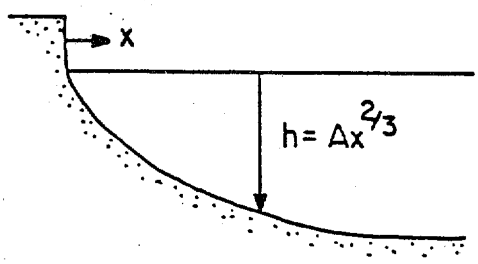
$$Q = K(D - D_*) \tag{2}$$

This form is similar to the sediment transport equation adopted by Swart (1974) which approximated Q based on the difference between actual and equilibrium geometric profile dimensions. In Equation (2), K is a

FIGURE 1

EQUILIBRIUM BEACH PROFILE CONCEPTS FOR NUMERICAL EROSION MODEL

I. EQUILIBRIUM BEACH PROFILE FORM

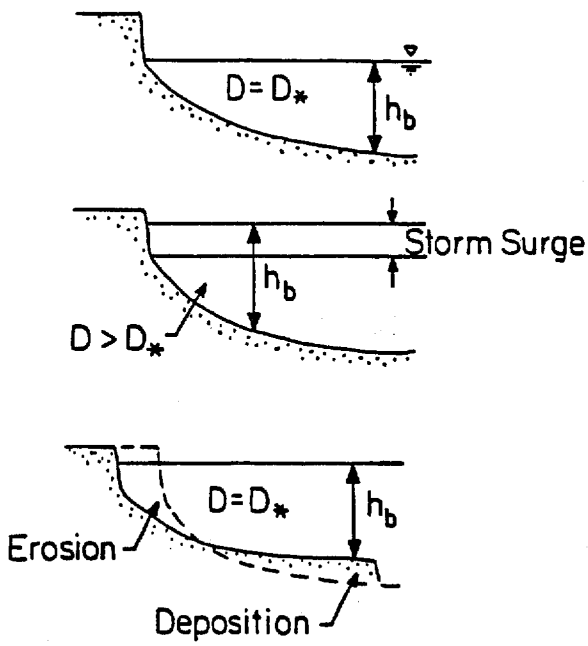


based on uniform energy dissipation per unit volume where A is related empirically to sediment size and can be related to D_* by:

$$A = \left(\frac{24}{5}\,\frac{D_*}{\gamma\kappa^2 g^{1/2}}\right)^{2/3}$$

II. ENERGY DISSIPATION PER UNIT VOLUME $D = \frac{1}{h}\frac{\partial F}{\partial x}$ where F is

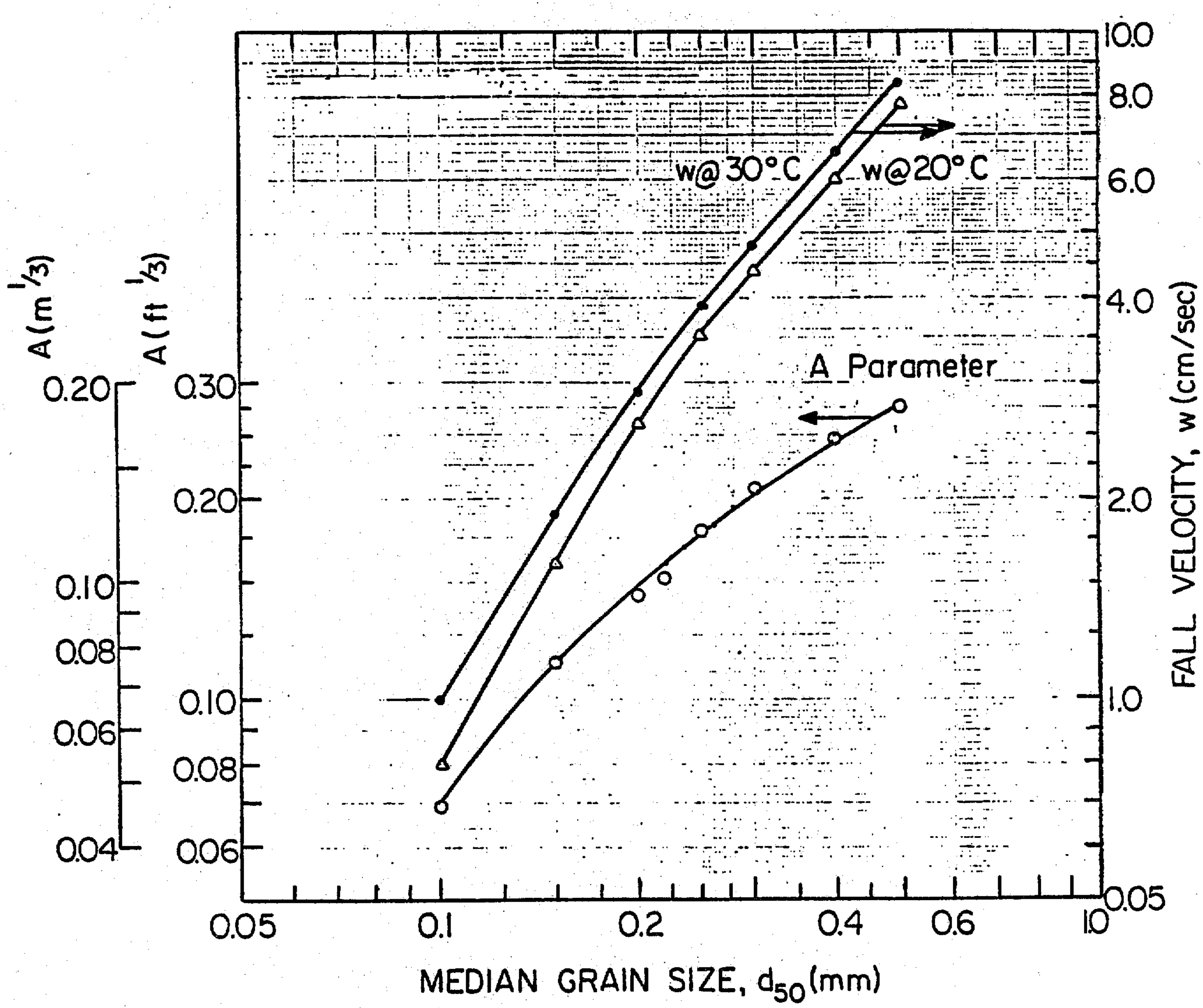
Energy Flux per unit crest length



III. SEDIMENT TRANSPORT EQUATION $Q = K(D - D_*)$

FIGURE 2

EQUILIBRIUM A PARAMETER AS A FUNCTION OF GRAIN SIZE AND FALL VELOCITY



proportionality factor that must be determined empirically based on a comparison of numerical results to observed profile response.

As a final general requirement for modeling profile response, the total sand volume in a beach profile must be conserved if it is assumed that there are no longshore transport gradients. For numerical simulation, the equation for continuity of sand in the onshore-offshore direction is

$$\frac{\partial x}{\partial t} = -\frac{\partial Q}{\partial h} \tag{3}$$

which is cast into an implicit, space-centered finite difference form. By numerically integrating this equation, together with the sediment transport equation, the change in position, x, of discrete depth contours is determined over each time step. In general since the actual energy dissipation D and sediment flux Q vary with water depth and bottom slope, the rate of change of each discrete contour differs from adjacent contours depending on water level, wave height, and profile form at the beginning of the time step. By inputting new water level and wave height conditions at each time step for the duration of a storm, the time-dependent beach and dune response during the storm may be estimated.

A description and verification of a numerical beach/dune erosion model based on the energy dissipation per unit volume and equilibrium beach profile concepts is presented by Kriebel (1982) and Kriebel and Dean (1984, 1985). Numerical results are shown to agree qualitatively with observed response characteristics of natural and laboratory beach profiles for a variety of water level, wave height, beach slope, and sediment characteristics. A preliminary quantitative verification of the model was carried out in a simulation of the time-dependent beach and dune erosion associated with Hurricane Eloise in Bay and Walton Counties in Florida. It was found that the model reasonably predicted the magnitude of average storm-induced erosion as the predicted volumetric erosion compared favorably with observed average eroded volumes as given by Chiu (1977). Dune steepening during erosion was not simulated, however, therefore predicted recession of specific evaluation contours did not agree as closely with observed values.

This verification was considered preliminary since no effort was made to simulate detailed response of individual pre-storm profiles or to compare predicted erosion to actual post-storm profiles. Instead, erosion was simulated using a single average pre-storm profile from the area of interest and results were then compared to the average profile response characteristics for the two-county area as given by Chiu (1977). After viewing 110 measured pre- and post-storm profiles for Walton County, it is evident that there is great variability in the response of individual profiles. In fact, over 20 profiles showed a net accretion between the two surveys in October 1973 and October 1975 (post-storm profiles were measured 2-4 weeks after Eloise). The possible inclusion of these profiles, and others which showed little erosion, in the average erosion statistics may skew these figures such that published average erosion characteristics are lower than the actual erosion experienced by many of the profiles, in many cases by more than a factor of two. These differences may be attributed in part to three effects: 1) pre-storm profile modification between October 1973 and September 1975, 2) localized longshore transport gradients during the storm, perhaps causing local accumulation of sand, and 3) beach recovery between the storm and the post-storm surveys. Chiu (1977) suggests that an average of about 50 ft^3/ft may have been returned above the mean sea level (MSL) contour following the storm but prior to the post-storm survey.

In order to obtain more realistic estimates of actual storm-induced erosion, the original erosion model described by Kriebel (1982) and Kriebel and Dean (1984, 1985) has been modified to include many effects not previously represented. Specifically, provisions are made in the updated model to include changing beach slopes and dune steepening to a near vertical slope. These changes permit a more realistic post-storm profile such that recession of individual elevation contours more closely agrees with nature. Along with these changes, a more complete verification of the model is made with actual pre- and post-storm beach profiles from the Hurricane Eloise data set. The revised model is first calibrated based on a large-scale laboratory experiment of Saville (1957) and is then recalibrated using a reference profile, line R-41, from the Walton County data set. Profile R-41 is used as a calibration standard since it was also used in two other dune erosion verification studies by Hughes and Chiu (1981) and Vellinga (1983a). Finally, the calibrated model is used to hindcast erosion for an additional 20 severely eroded profiles from the Walton County data set in an effort to test model sensitivity and bias introduced in the calibration process.

Modified Beach/Dune Erosion Model

Beach slope changes and dune steepening are introduced into the erosion model based on geometrical arguments similar to those used by Bakker (1968), Swart (1974), and Perlin and Dean (1983) in other simple numerical schemes for simulating offshore sediment transport. In general, it is assumed that the distribution of sediment transport on the active beach face is proportional to the volumetric difference between the existing profile and an assumed maximum potential erosion profile for the same region above the still water level. This maximum potential erosion profile is based on known equilibrium slopes and the vertical extent of the active profile. The method therefore requires input of the equilibrium slopes of the active beach and dune face and approximate runup elevations.

In the original numerical model by Kriebel and Dean (1984, 1985), the sediment transport distribution on the active beach or dune face was approximated by a straight-line extension of the Q curve from its calculated value, Q_*, just below the still water level, to zero at the upper limit of the active profile which was taken as either the berm or the dune crest as in Figure 3. This linear extension resulted in constant spatial gradients in the Q curve, $\partial Q/\partial h$, which then gave uniform retreat of the beach or dune face based on the continuity equation:

$$\frac{\partial x}{\partial t} = - \frac{\partial Q}{\partial h} = \text{constant}$$

Because this uniform retreat, initial beach and dune slopes were maintained above the depth h_*, therefore precluding simulation of slope steepening and dune scarps.

In the modified erosion model used in this study, the transport curve is not extended linearly and, instead, an estimate of the sediment transport distribution is obtained in the following manner:

1) The water level is established and three points in the profile are located as shown in Figure 4. The depth h_b is established as the breaking depth of incident waves based on the spilling breaker assumption, i.e., $h_b = 1.28\ H_b$. The depth, h_* is established at the depth in which the equilibrium beach face slope is tangent to the equilibrium $Ax^{2/3}$ profile form such that there is a monotonic decrease in bottom slope from the beach face to the breakpoint. The elevation h_u is then established at the upper limit of the active profile. This upper limit is assumed to be the berm crest, the runup limit on the dune, or the top of the dune scarp after a scarp is formed.

2) Based on the governing equations, energy dissipation per unit volume and the sediment transport rate Q are calculated in the submerged portion of the profile from h_b to h_*. The calculated value of h_*, denoted Q_*, then represents the volume of sand per unit time that must be eroded from the "dry" beach face, between h_* and h_u, and which must flow past depth h_* over the time step. The estimated volume of sand eroded from the "dry" beach face over the time step is then:

$$V_* = Q_* \Delta t$$

3) Next, the maximum potential eroded volume, V_p, or the potential erosion prism of the "dry" beach is estimated between h_u and h_*. This is accomplished simply by establishing the known equilibrium beach or dune slopes relative to the known active limits. In Figure 5, Case I indicates that for an equilibrium slope m_* steeper than the actual slope m, the potential erosion prism is established by taking m_* relative to the upper limit, h_u, such that volume V_p is the potential eroded volume. In Case II, if m_* is less than m, then upper portions of the profile have a greater erosion potential than the contours near h_*, therefore, the equilibrium slope is taken relative to h . In Case III, if the actual slope is already in equilibrium, then it is assumed that all contours have an equal erosion potential. Since only a finite volume of material from the potential erosion prism may pass depth h_*, it is clear that the entire potential eroded volume V_p may not be eroded in a

FIGURE 3

PREVIOUS METHOD OF ESTIMATING DISTRIBUTION
OF SEDIMENT TRANSPORT ON BEACH FACE

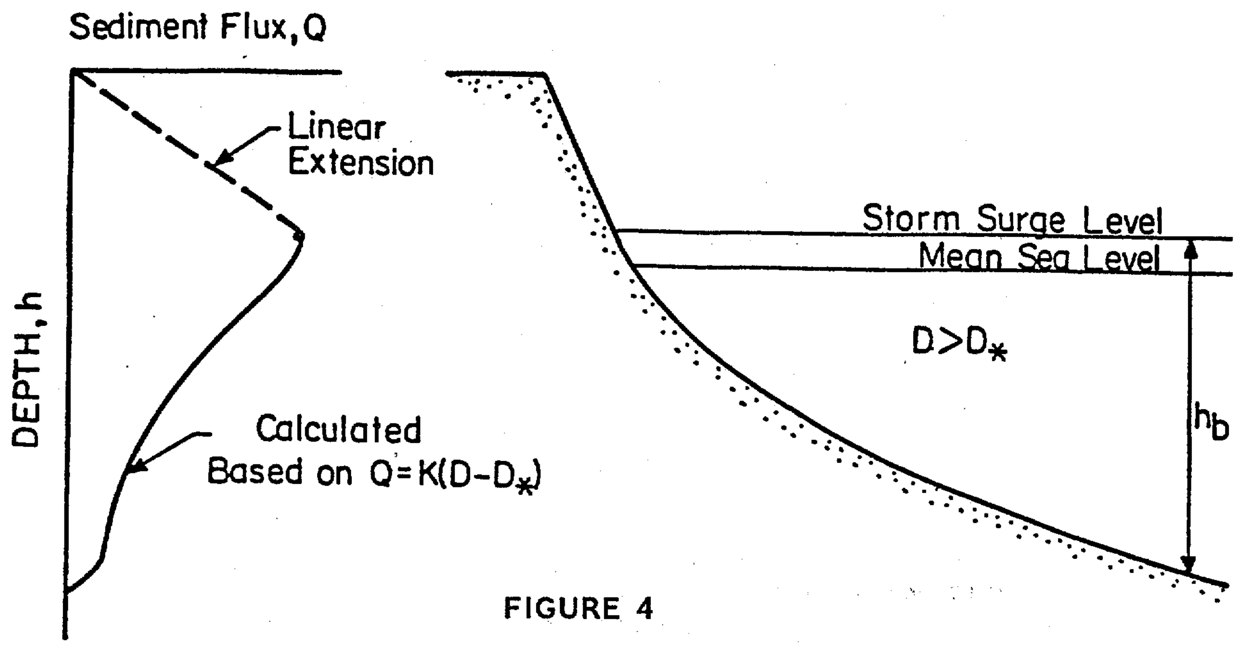


FIGURE 4

DEFINITION SKETCH OF SCHEMATIC BEACH PROFILE

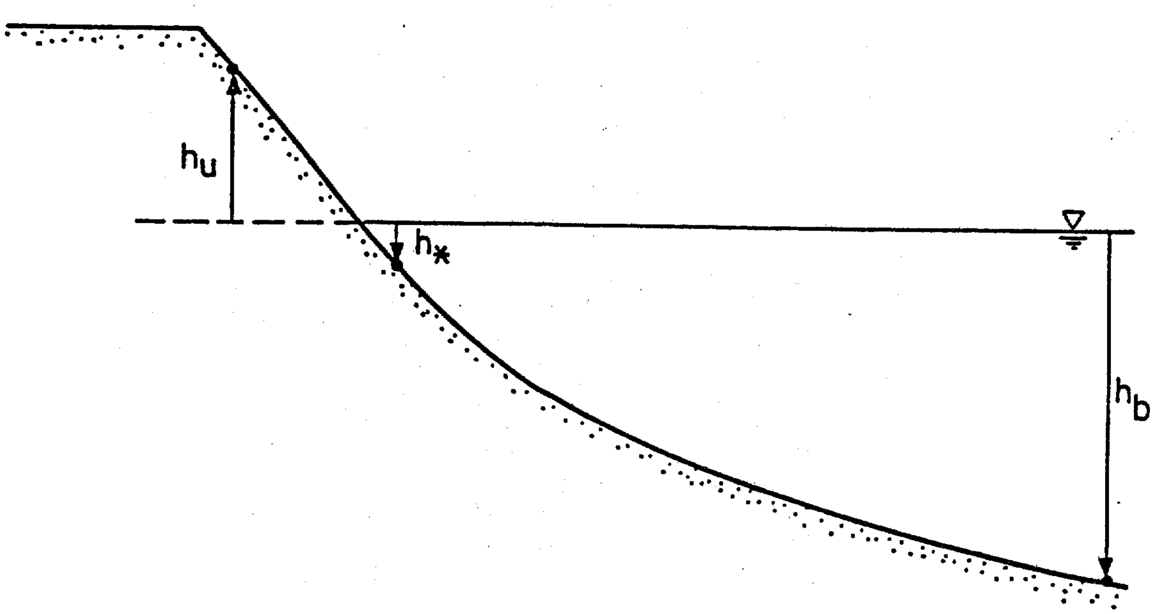
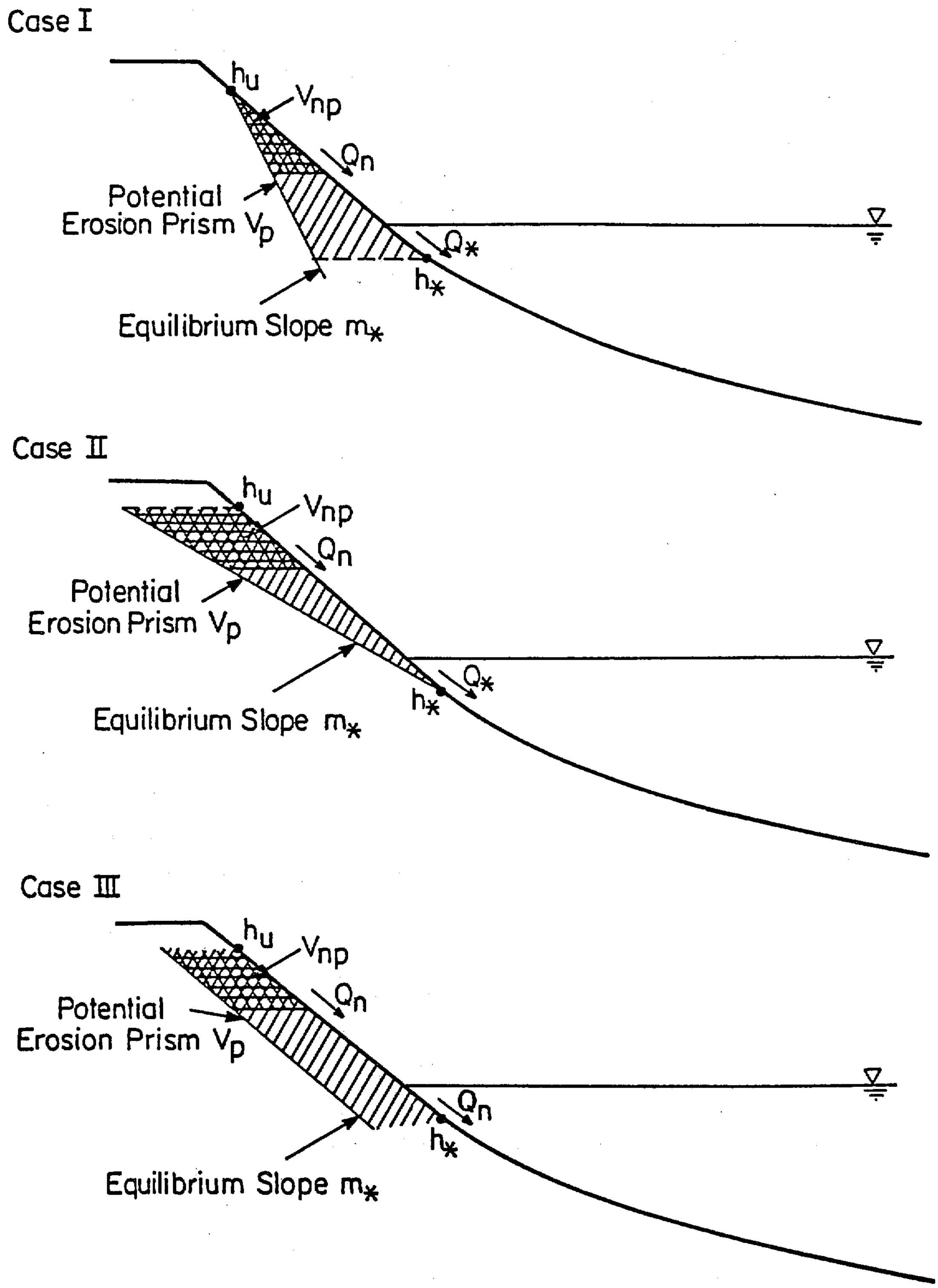


FIGURE 5

NEW METHOD OF ESTIMATING DISTRIBUTION OF SEDIMENT TRANSPORT ON BEACH FACE



single time step. In effect only the fraction V_*/V_p may be eroded over the time step.

In some cases, the potential erosion prism for Case I or Case II may not be large enough to provide the required volume V_*. In these situations, the additional required volume is obtained by translating the equilibrium beach slope landward. In this way combinations of Cases I and III as well as Cases II and III are used to obtain the final potential volume V_p which is identically equal to the required volume V_*.

4) The estimated distribution of sediment transport on the beach face is then estimated according to the fraction V_*/V_p of the potential volume that may be eroded above contour n. Denoting the potential volume above a point, n, as V_{np} the estimate of the eroded volume is

$$V_n = V_{np} \frac{V_*}{V_p}$$

and the estimate of the transport rate at n is

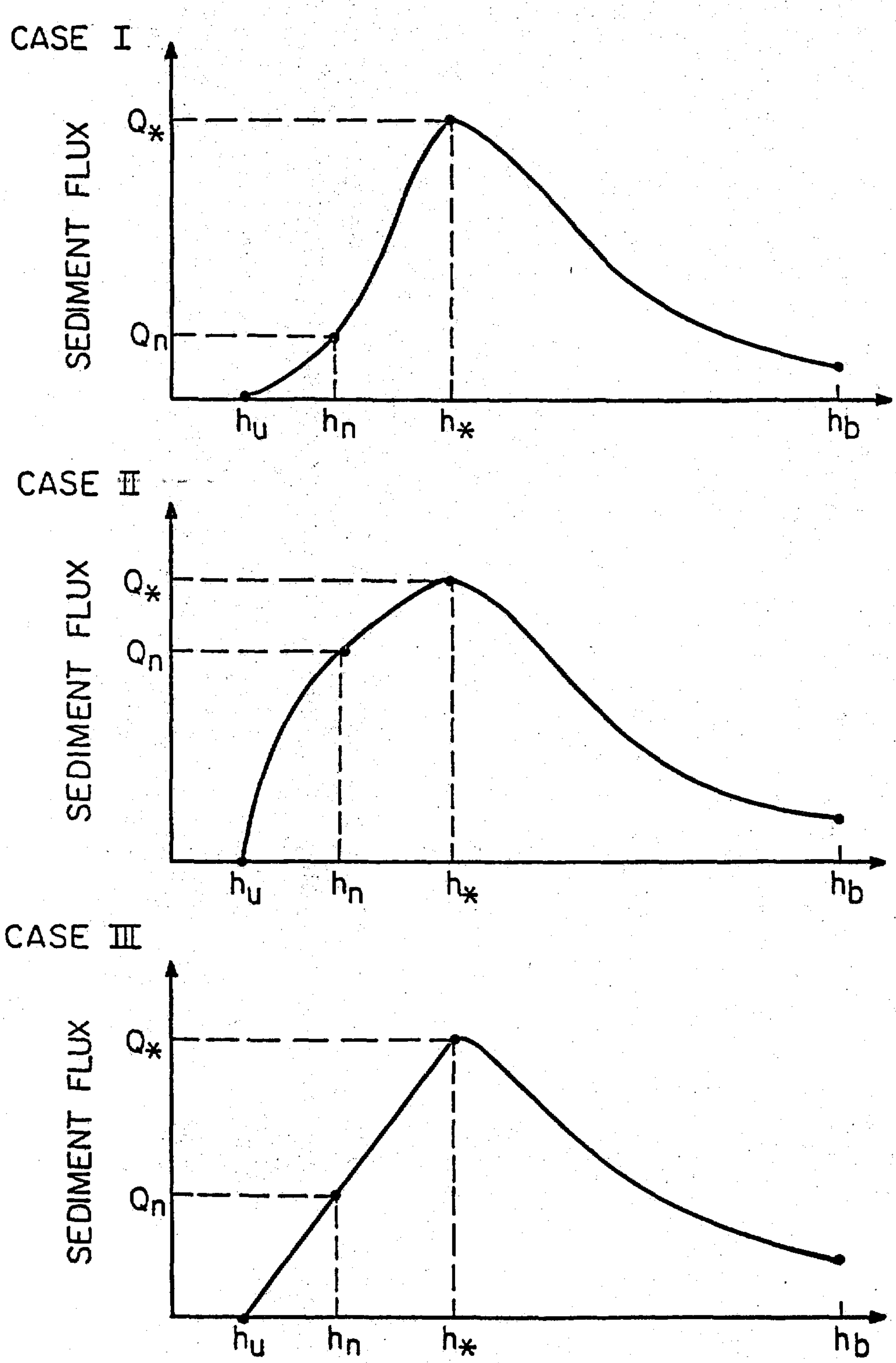
$$Q_n = \frac{V_n}{\Delta t}$$

For Cases I and II, this method gives the estimated transport distributions shown in Figure 6. For Case I, since the beach is assumed to steepen, transport gradients are greatest near the still waterline and decrease to near zero at h_u. For Case II, since the beach is assumed to become less steep, the largest transport gradients occur near the depth h_u and decrease to h_*. For Case III, since uniform erosion is expected, the distribution of Q is a straight line as in the original model.

5) During the simulation the "dry" beach face evolves toward the specified equilibrium slopes while the submerged portion of the profile, between h_* and h_b, evolves toward the equilibrium $Ax^{2/3}$ configuration. On the "dry" beach face, estimated Q values are also converted to equivalent D values based on the transport equation. The numerical double-sweep procedure, described by Kriebel (1982) is then applied over the entire active profile from h_u to h_b therefore ensuring continuity both in terms of the sand volumes eroded/deposited but also in terms of linking the, solutions for the geometric (dry) and dynamic (submerged) regions.

FIGURE 6

EXAMPLES OF ESTIMATED SEDIMENT TRANSPORT
DISTRIBUTIONS ON BEACH FACE



SECTION II

CALIBRATION - SAVILLE'S LABORATORY EXPERIMENT

Background

The modified erosion model is tested and calibrated based on numerical simulations of Saville's (1957) large-scale laboratory experiments. The model calibration is performed by varying the free coefficient, K, in the sediment transport equation until best-fit, in the least squares sense, is obtained between predicted and observed beach profile response. Saville's experiments provide a useful data set for testing the numerical erosion model because they were conducted at approximately full-scale and because detailed measurements were made throughout the profile development from which time-dependent erosion characteristics, including beach slope steepening, can be tested.

Based on copies of Saville's laboratory notes, initial conditions for test #3 at prototype scale are:

Beach Slope	1:15
Water Depth at toe of slope	14 feet
Berm Crest above Still Water Level	6 feet
Median sand diameter	0.22 mm
Wave height	5.5 feet
Wave period	11.33 sec
Breaker height	6-7 feet
Breaking depth	6 feet
Test duration	50 hours

Approximate equilibrium occurs after about 40 hours with only a minor shifting of offshore bars occurring between 40 and 50 hours. Waves in the experiment quickly shoaled on the steep seaward toe of the developing profile such that plunging breakers with heights of 6 to 7 feet are reported by Saville. However, the breaking depth and location relative to the outer bar crest also remained fairly constant. In the numerical model the apparent breaking depth of 6 feet is used to establish the seaward limit of the concave $Ax^{2/3}$ profile at equilibrium.

Calibration Procedure

For calibration of the numerical erosion model, all physical parameters must be specified so that the transport coefficient, K, remains as the only parameter to be determined. Required physical parameters include the initial profile form (1:15 slope), the characteristic A parameter, the equilibrium slopes, runup distance, and breaking depth. Based on Saville's final equilibrium profile, the equilibrium beach face slope is approximately 1:5 and the vertical runup distance above the still water level is 4 feet. Seaward of the breakpoint, the offshore slope is approximated by a uniform slope of 1:5. The scaling parameter, A, is then determined by a least-squares fit of the $Ax^{2/3}$ profile form to the observed profile at 40 hours and the best-fit A value is found to be 0.160 $ft^{1/3}$. Based on results from over 700 open-coast beach profiles analyzed by Dean (1977), Hughes (1978), and Moore (1982), the

0.22 mm sand used by Saville should correspond to $A = 0.155\ ft^{1/3}$. Given the close agreement between these two independent estimates, the value used for calibration is $A = 0.160\ ft^{1/3}$ as obtained from a direct $Ax^{2/3}$ curve-fit to Saville's equilibrium barred profile.

Calibration of the erosion model is accomplished by a series of simulations in which separate values of K are used to simulate Saville's profile development while all other parameters are held constant. The eroded volume at any time is determined as the cumulative volume of material displaced between the initial profile and the profile at the current time. The mean squared error between the predicted and observed eroded volumes is then obtained after 5, 10, 15, 20, 25, 30, 35, 40, and 50 hours as

$$\overline{\varepsilon_N^2} = \frac{1}{N} \sum_{n=1}^{N} [(V_{pred})_n - (V_{obs})_n]^2$$

Because all other parameters are held constant and are best-fit values obtained from Saville's equilibrium profile, it is expected that a distinct best-fit K may be obtained. In Figure 7, results from the calibration test series are summarized with the mean squared error plotted for eight K values tested. The five curves shown correspond to the error curves obtained after 10, 20, 30, 40, and 50 hours of simulation since it is desired to determine an overall K which provides best agreement over the duration of the experiment, not just after equilibrium is attained at 40 to 50 hours. After 10 hours the best-fit K is 0.004 to 0.0045 ft^4/lb while from 20 to 50 hours, minima of the error curves occur between 0.0045 and 0.005 ft^4/lb. In general, the broad troughs of the mean squared error curves indicate that varying K by ± 10 percent is not critical and will give similar results for erosion estimates. Based on these results, an overall value of $K = 0.0045\ ft^4/lb$ is adopted which seems to give near minimum error over all time scales of interest. The observed and predicted cumulative erosion curves are shown in Figure 8 based on the selected best-fit value of K.

In Figure 9, the predicted profile is compared to Saville's measured profile after 40 hours. In general, the monotonic curve approximates the development of the barred profile quite well in a volumetric sense and in terms of the width of the surf zone. In the numerical simulation, the shoreline does not steepen as quickly as the laboratory profiles of early times; however, at equilibrium the simulated beach face actually recedes 4 to 5 feet farther than the laboratory profiles. In Figure 10, the numerical evolution of the profile, including the steepening beach face, seems realistic and provides a confirmation that the sediment transport distributions used in the model are reasonable approximations.

FIGURE 7

MEAN SQUARE ERROR OF VOLUME ERODED VERSUS SEDIMENT TRANSPORT COEFFICIENT K

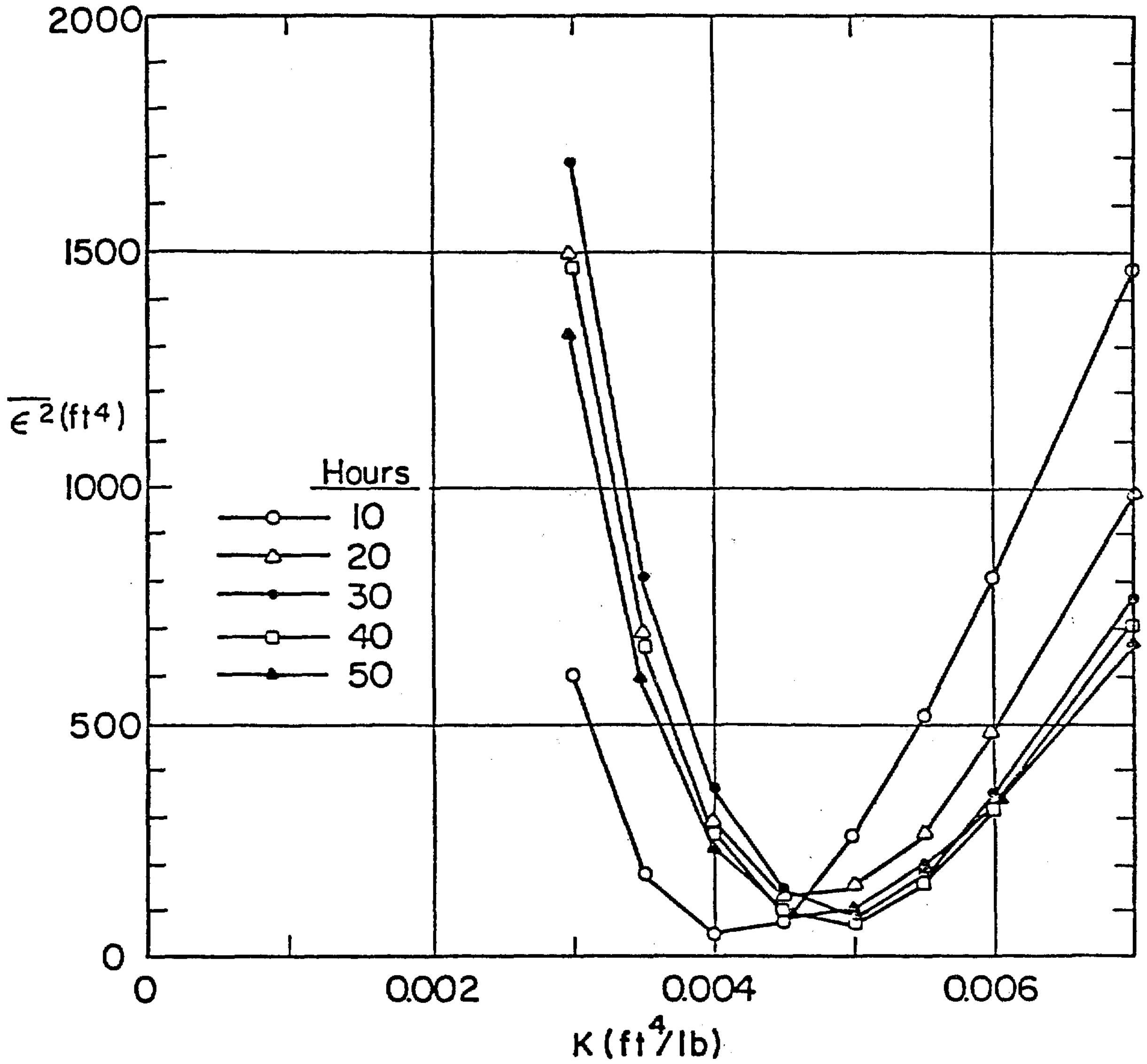


FIGURE 8

COMPARISON OF CUMULATIVE EROSION: CALIBRATED MODEL VERSUS SAVILLE'S (1957) LABORATORY EXPERIMENTS

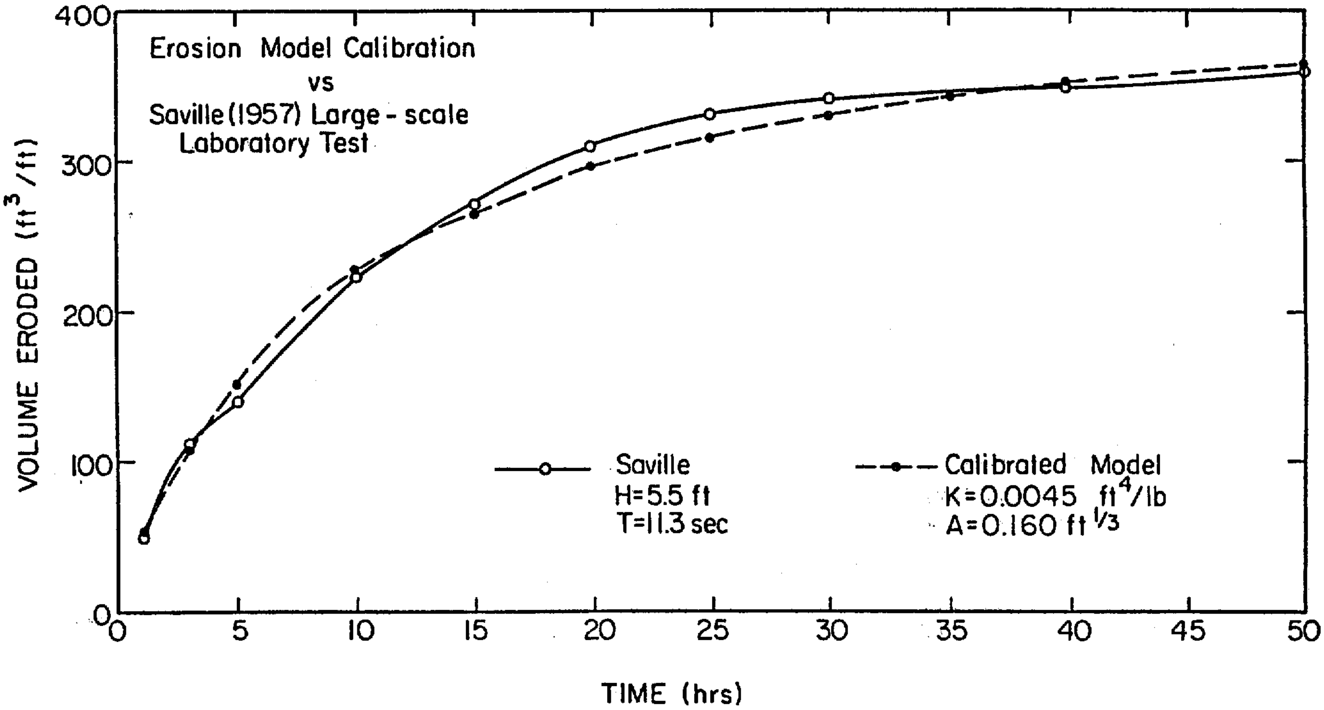


FIGURE 9

COMPARISON OF PROFILE FORMS: CALIBRATED MODEL VERSUS SAVILLE'S (1957) LABORATORY EXPERIMENTS

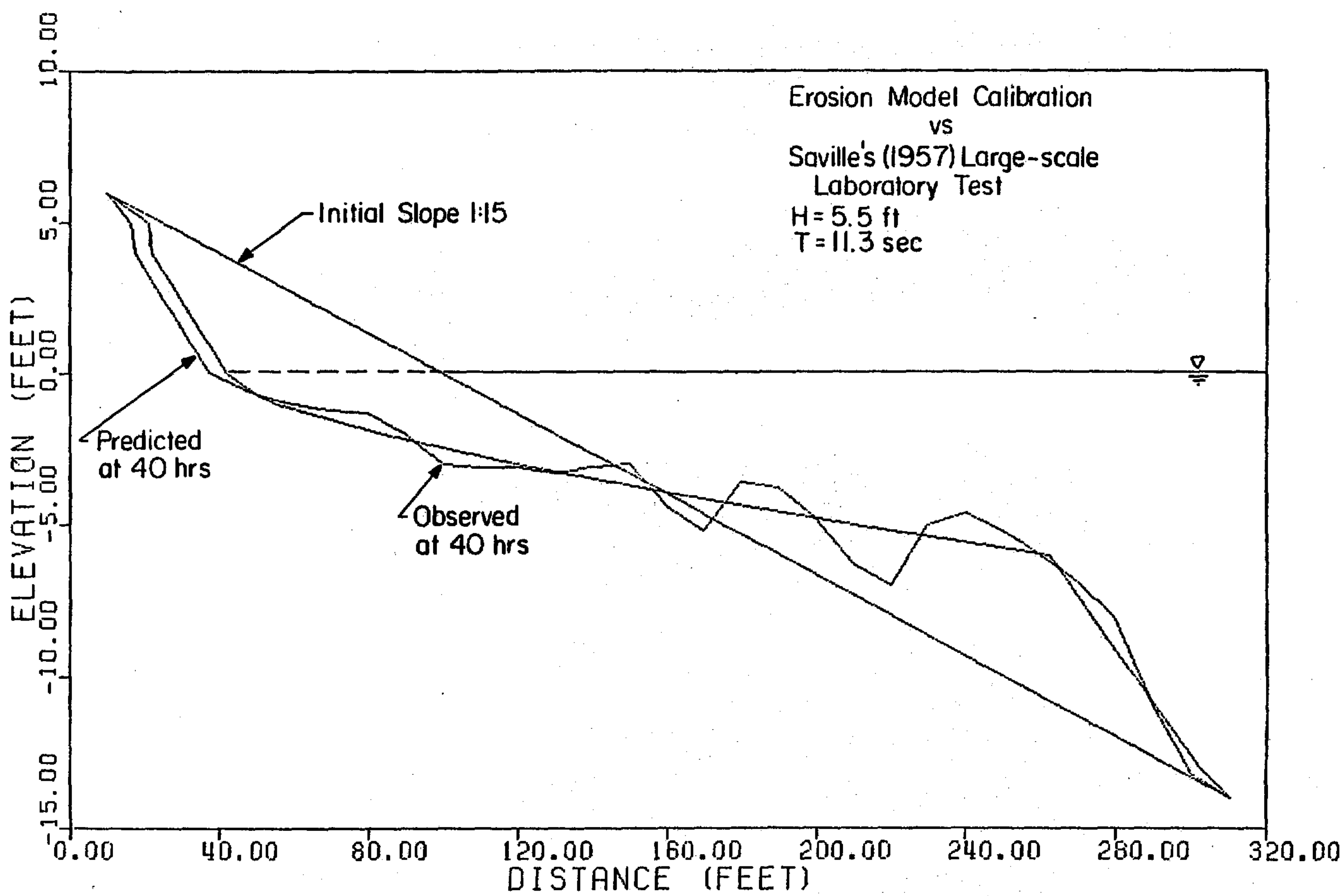
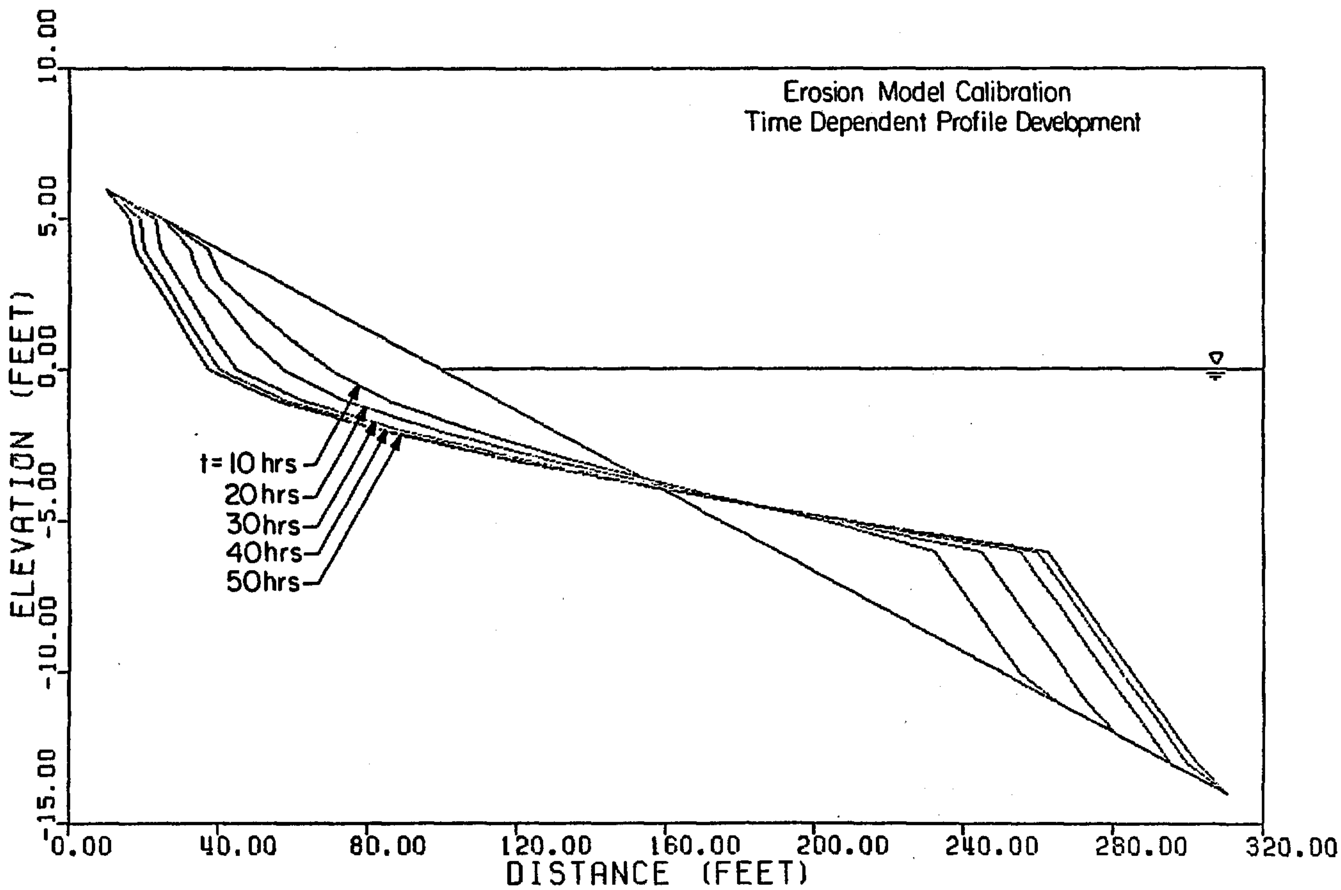


FIGURE 10

TIME-DEPENDENT EVOLUTION OF PREDICTED PROFILE



SECTION III

CALIBRATION - HURRICANE ELOISE FIELD DATA

Background

Hurricane Eloise made landfall just east of Walton County on September 23, 1975, and was a rapidly moving storm which, while lasting less than 20 hours, produced estimated peak water levels of between 8 and 10 feet over Walton County. Although no open-coast storm surge measurements are available, numerical estimates by Dean and Chiu (1984) range from 8.35 feet at the western end of Walton County to 9.60 feet at the eastern end of the county. The predicted storm surge hydrograph near the western end of Walton County is shown in Figure 11. Significant wave heights recorded during the peak of the storm are 10 to 14 feet with a dominant period of 11 seconds. For this study, a significant wave height of 12 feet is used to obtain an estimate of the offshore limit of sediment deposition.

Pre-storm profiles for the Walton County area are taken from the October 1973 survey of the area by the Florida Department of Natural Resources. Post-storm surveys were conducted within 3-4 weeks after the storm in October 1975. Due to the timing of these surveys, the "observed" erosion associated with Hurricane Eloise may be contaminated by two effects. First, it is probable that some modification of the pre-storm profile occurred in the two years between October 1973 and September 1975. These effects may include natural erosion or accretion of the shoreface and possible modification of the dunes by wind-blown sand or construction activities. Second, in the 3-4 weeks after the storm, some recovery of the shoreface certainly occurred. Chiu (1977) estimates that 240,000 yd^3 had returned to the beach face over Walton County, and profiles show a distinct berm of about 30 to 60 ft^3/ft between 0- and 4-foot elevations. When discussing agreement between the observed erosion characteristics and any erosion prediction model, these two effects must be considered.

Two previous studies of beach/dune erosion have used profile R-41 from Walton County, Florida, for model verification in reproducing prototype storm related erosion. Hughes and Chiu (1981) selected R-41 as a representative profile to be used in verification of small-scale laboratory simulations of dune erosion. Vellinga (1983a) also used R-41 as a part of a continuing verification of a computational method for predicted dune erosion due to severe storms. Since profile R-41 has now become in some respects the standard reference profile from the Hurricane Eloise data set, it seems reasonable to test and calibrate the numerical erosion model based on this profile as well. In this study, however, the erosion model is also tested against 20 additional profiles from the Walton County data set to determine possible bias associated with using R-41 as a benchmark for calibration/verification.

The pre- and post-storm profiles for range R-41 are shown in Figure 12. This profile is fairly representative of the Walton County area in that it has broad well-developed dunes, and a narrow berm with a berm crest elevation of 5 to 6 feet. The post-storm profile is typical in that a distinct break in

FIGURE 11

HURRICANE ELOISE STORM SURGE HYDROGRAPH
From Dean and Chiu (1984)

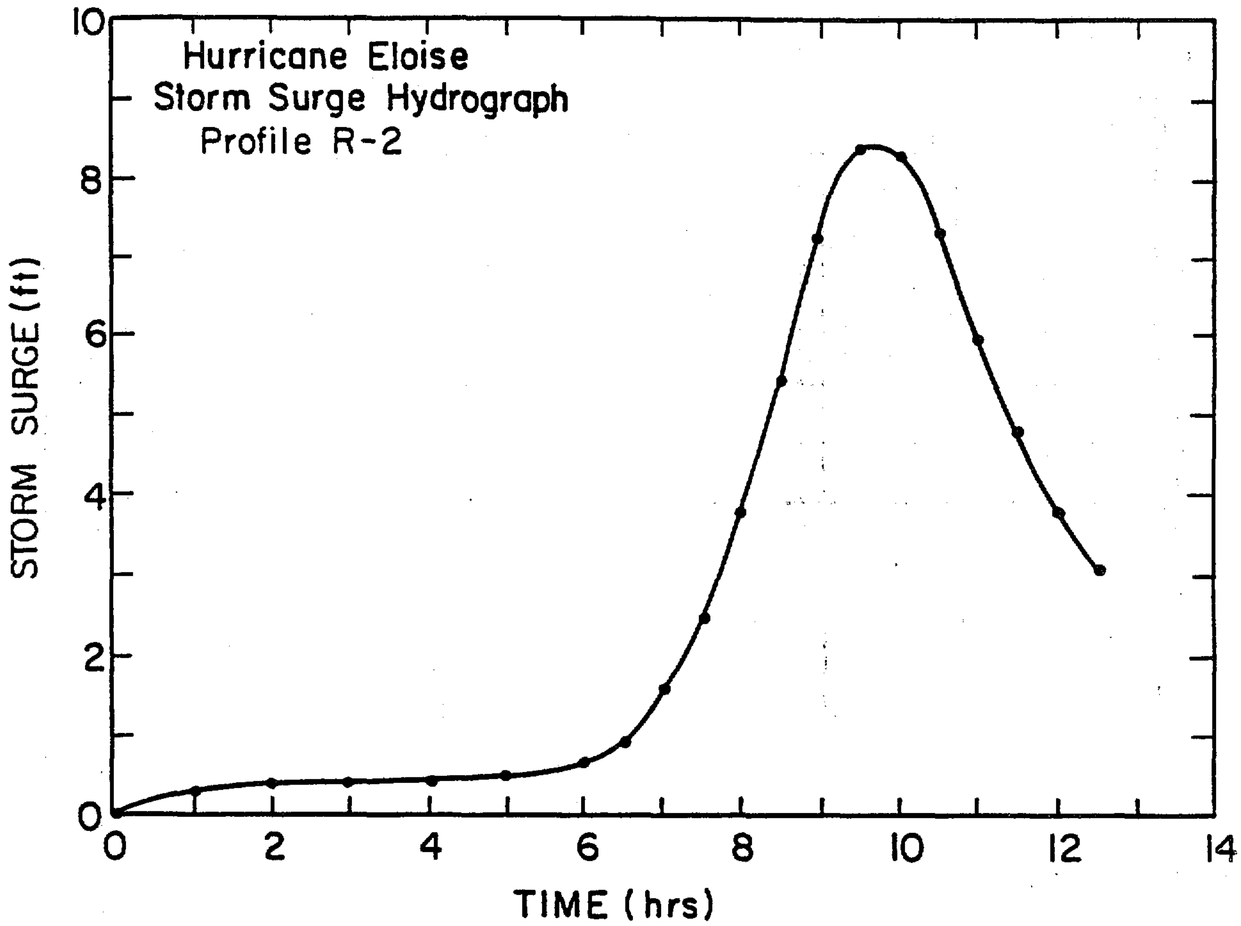
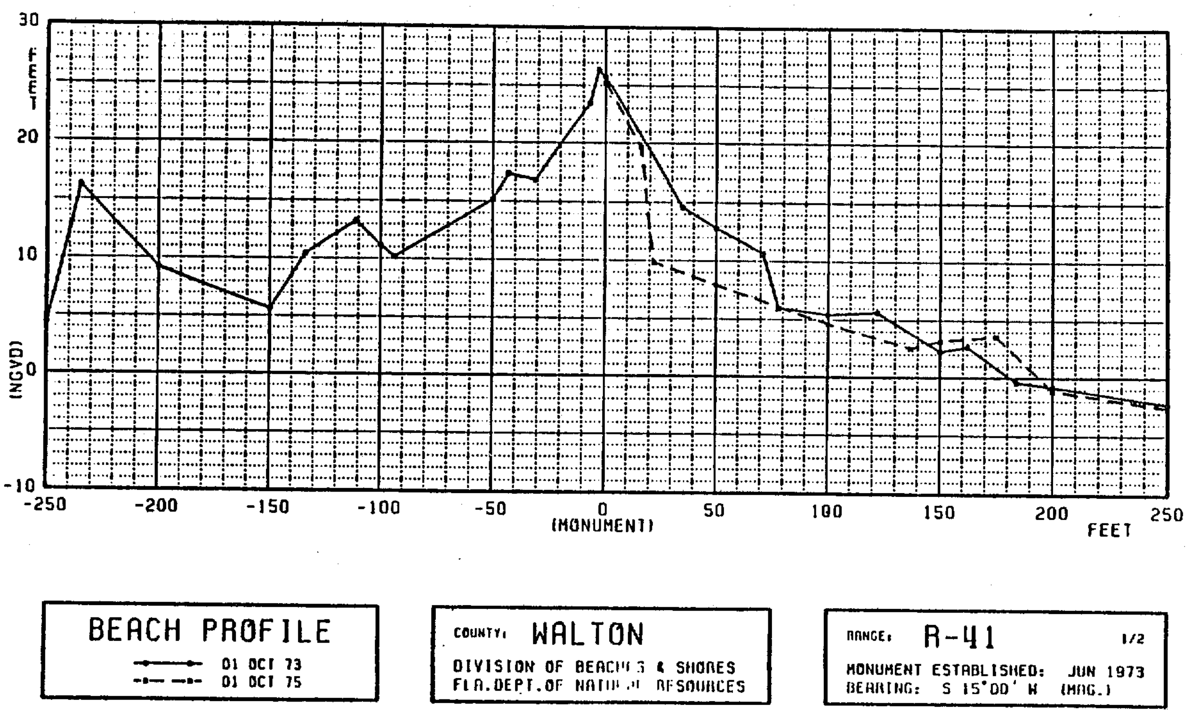


FIGURE 12

PRE- AND POST-STORM BEACH PROFILE, PROFILE R-41, WALTON COUNTY, FLORIDA
From Florida Department of Natural Resources



slope occurs between the dune scarp and the flattened beach at about 10 feet. The rebuilt post-storm berm is also clearly evident. The computed eroded volume of about 400 ft^3/ft above the 0-foot contour is perhaps above average for the entire data set. As noted earlier 20 profiles showed a net accretion between October 1973 and October 1975. However, R-41 is not the most severely eroded profile in Walton County.

In this study, water level and wave conditions are assumed to be reasonably represented by the storm surge hydrograph in Figure 11 and by a significant breaking wave height of 12 feet. It should be noted that the storm surge elevations have been interpolated by Dean and Chiu for all 125 profiles in Walton County and the surge hydrograph in Figure 11 is multiplied by the appropriate factor to give the hydrograph for each site. For profile R-41, the surge hydrograph is multiplied by 1.083 at all times.

Offshore profile forms for pre-storm conditions are assumed to be in equilibrium and characterized by an $Ax^{2/3}$ profile. The scaling parameter A may be determined from Figure 2 based on the effective grain size of 0.262 mm given by Hughes and Chiu (1981). In this case the appropriate A value is 0.184 $ft^{1/3}$. Hughes and Chiu model the profile form based on a fall velocity of 4.0 cm/sec for 25°C water while Vellinga (1983a) models the same profile based on a fall velocity of 3.6 cm/sec. In Figure 2, these fall velocities correspond to A values of 0.170 $ft^{1/3}$ to 0.195 $ft^{1/3}$ for 20°C to 30°C water temperatures. Since A = 0.184 $ft^{1/3}$ lies within this range and is especially good for 25°C temperatures, this value is adopted in this study.

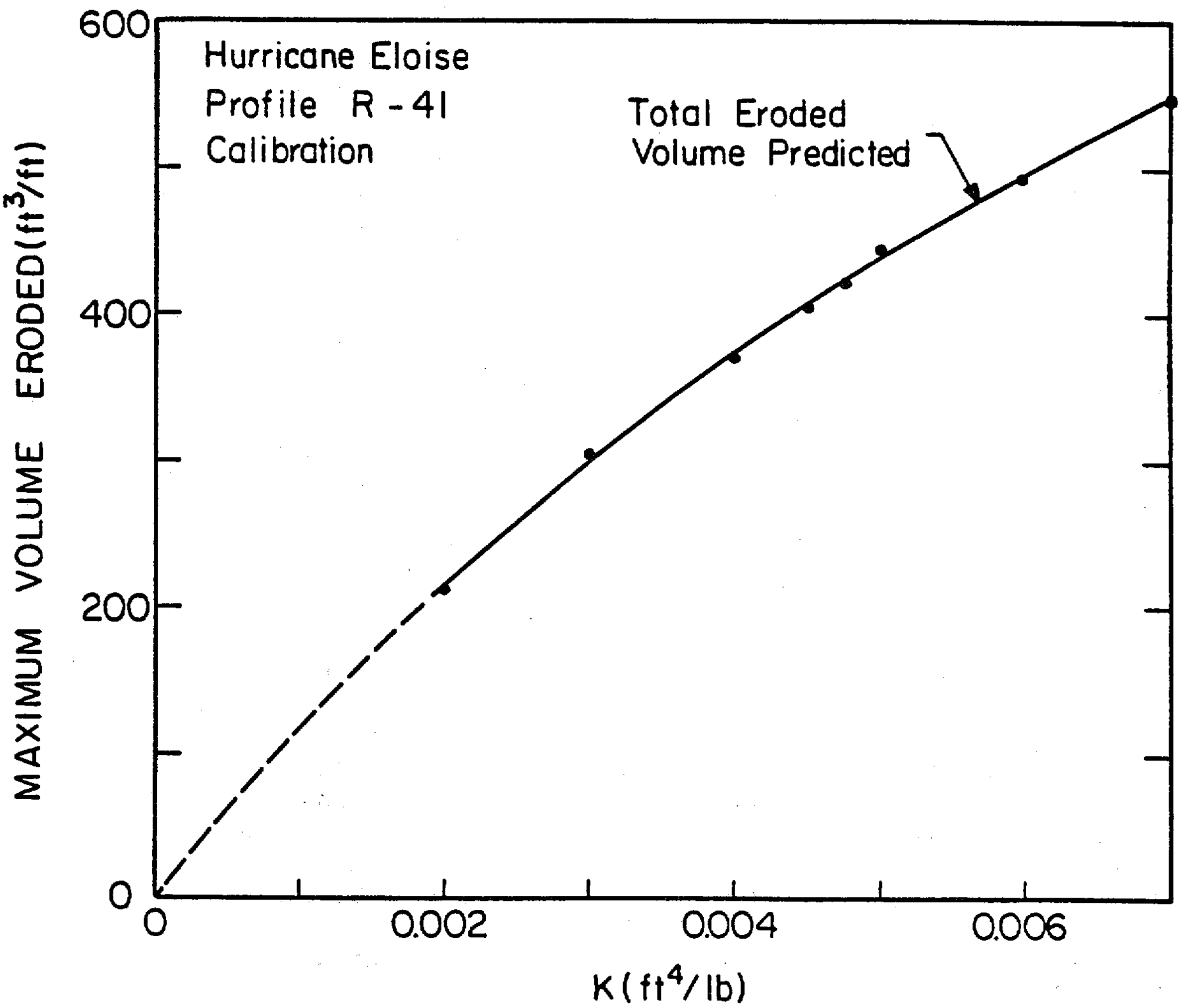
Calibration/verification of the numerical erosion model is first carried out on profile R-41. In this case, input to the numerical model consists of the actual pre-storm profile between the dune crest at 26 feet and mean sea level, taken to be at 0 feet (National Geodetic Vertical Datum) NGVD. The offshore profile is established according to $h = 0.184\ x\ ^{2/3}$ out to depths of 20 feet. Additional required input consists of the "equilibrium" slopes of the dune scarp and beach face as well as an effective runup height. Based on Figure 12, the equilibrium dune slope is taken as 1.75:1, a 1-foot runup is assumed (based on peak surge elevation of 9.03 feet and a break in slope at 10 feet), and the post-storm beach face slope is taken to be 1:15. Slopes seaward of the breaking depth are set at 1:15.

Calibration Procedure Using Profile R-41

Due to the uncertainties involved in the post-storm eroded volumes, calibration of the erosion model is obtained in a more subjective manner than in the previous calibration against Saville's data. In this case, since the estimate of total eroded volume (400 ft^3/ft) may not exactly represent the actual eroded volume, and since the time-history of erosion is not available, the mean squared error curves as a function of K cannot be developed. Instead, in Figure 13, predicted maximum volumetric erosion is plotted against the value of K used in each test, and a smooth curve is drawn through the data points.

FIGURE 13

PREDICTED VOLUME ERODED FOR PROFILE R-41
VERSUS SEDIMENT TRANSPORT COEFFICIENT K



Based on the 400 ft^3/ft estimate of total observed eroded volume, the best prediction is obtained using a value of $K = 0.0044\ ft^4/lb$; within arbitrary 10 percent error bands, the best K values range between 0.0038 and 0.0052 ft^4/lb. From this analysis, a value of K between 0.004 and 0.005 ft^4/lb seems most appropriate. This range is identical to that suggested by the calibration based on Saville's profile and the previous best estimate of $K = 0.0045\ ft^4/lb$ seems equally appropriate for profile R-41. This surprising agreement between the two calibration runs is fortuitous and should not be taken as an absolute indication that $K = 0.0045\ ft^4/lb$ is the "correct" or universally valid constant for the proposed erosion model. Most likely, the agreement is the result of assumptions made in each simulation concerning input parameters.

As a sensitivity test, erosion estimates for R-41 are obtained using various wave height scenarios. In Figure 14, the eroded volumes obtained by using a constant wave height over the duration of the storm surge are compared to estimates obtained by applying a variable wave height. Variable wave heights are scaled from 3 feet to the maximum height shown according to the ratio of the storm surge level at each time step to the peak surge level. Results of this test indicate that a variation in the constant wave height of ± 20 percent produces less than a 5 percent change in eroded volume. Likewise, use of a variable wave height tends to decrease the erosion estimate by only 5 percent for the range of wave heights of interest. If calibration had been carried out using a variable wave height, a slightly larger volume of K would have been required. Due to the small differences between predictions, all model calibration, verification, and application is performed with a constant wave height.

In Figure 15, the predicted post-storm profile is compared to the observed post-storm profile form for $K = 0.0045\ ft^4/lb$. There is good agreement between predicted and observed profiles from the base of the dune scarp across the shoreface to the point where the berm built by post-storm recovery occurs. The major difference between the predicted and observed profiles is the predicted position of the dune scarp, which is about 3 to 4 feet seaward of its actual position. In this case, a slightly larger value of K would provide the best agreement with the observed dune scarp.

The time variation of the numerical simulation is depicted in Figure 16. The predicted profile position is shown after 8, 10, 11 and 12.5 hours of simulation corresponding to water levels of 4.06,8.99, 6.47, and 3.28 feet respectively. While the maximum dune recession occurs at 11 hours or 1.5 hours after the peak surge, the maximum eroded volume occurs at 12.5 hours as a small amount of sand is eroded from lower portions of the beach face as the water level recedes. In Figure 17, the entire active profile is shown. Because of the changing water levels and, therefore, the changing position of the breaking depth, the offshore portion of the profile is smooth with no discontinuities as would be obtained from a steady-water level estimate as in the simulation of Saville's profile development.

FIGURE 14

SENSITIVITY OF PREDICTED VOLUME ERODED
TO WAVE HEIGHT DESCRIPTION

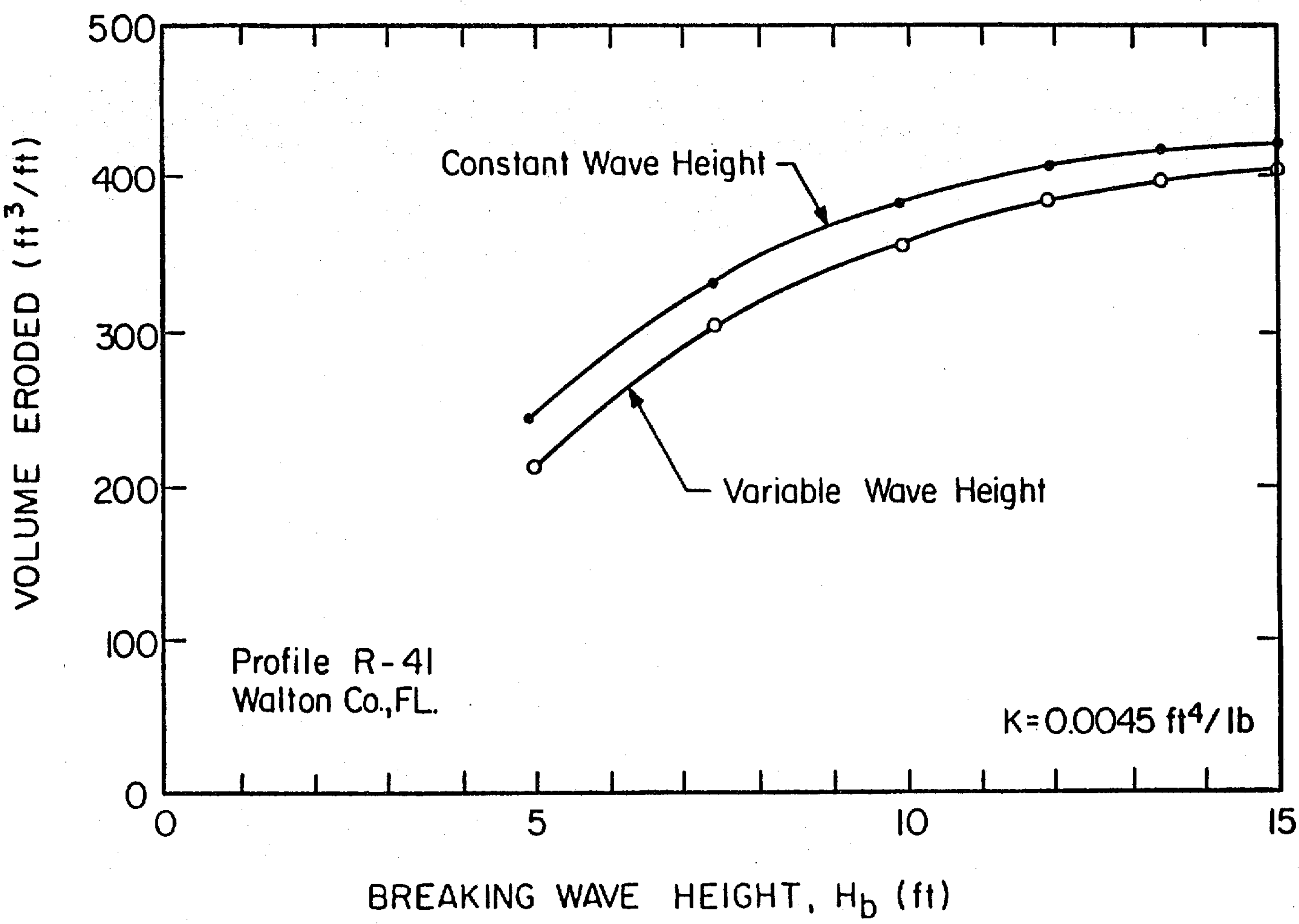


FIGURE 15. COMPARISON OF PREDICTED TO OBSERVED POST-STORM PROFILE FORMS

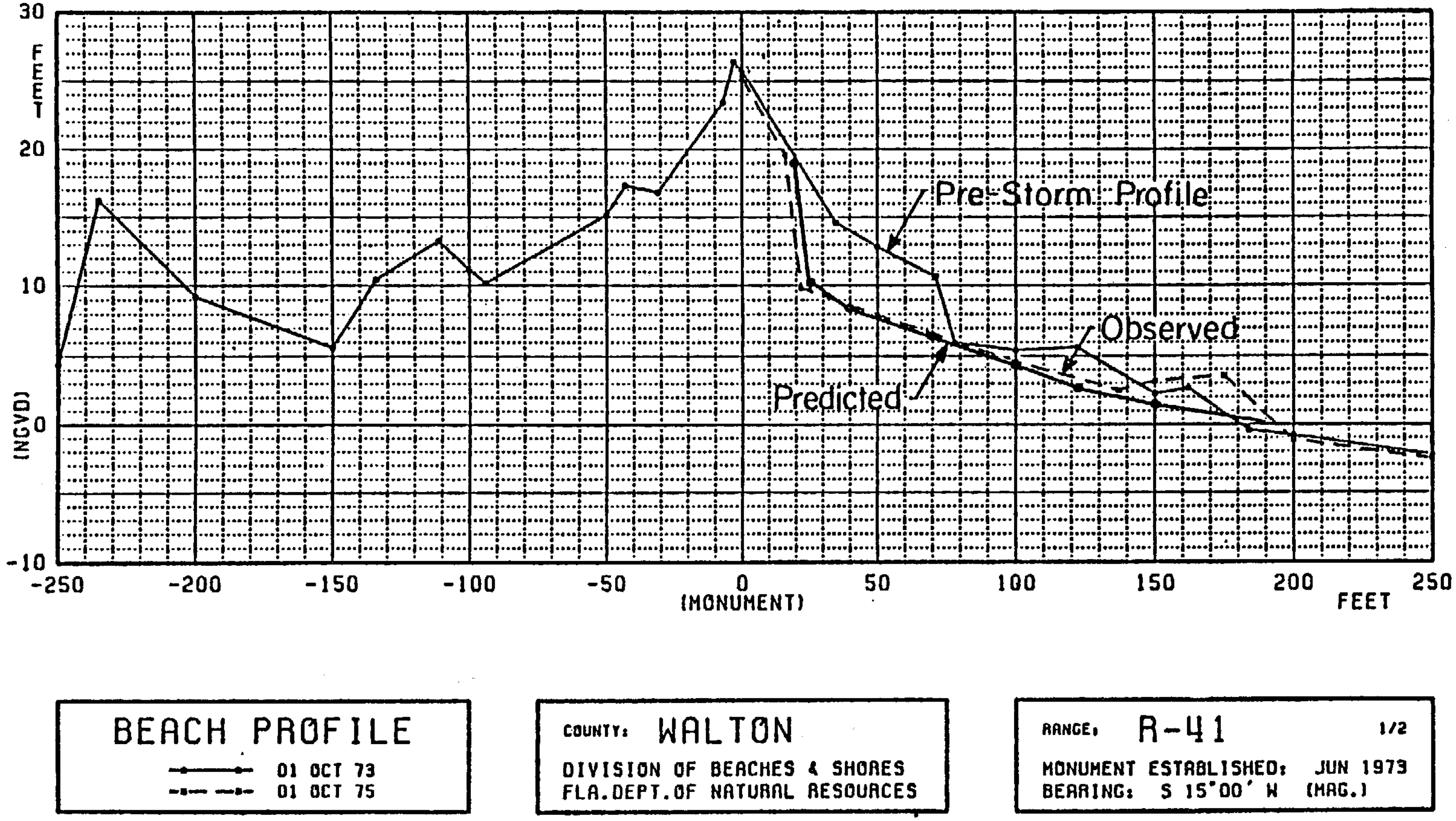


FIGURE 16. TIME-DEPENDENT EVOLUTION OF PREDICTED PROFILE

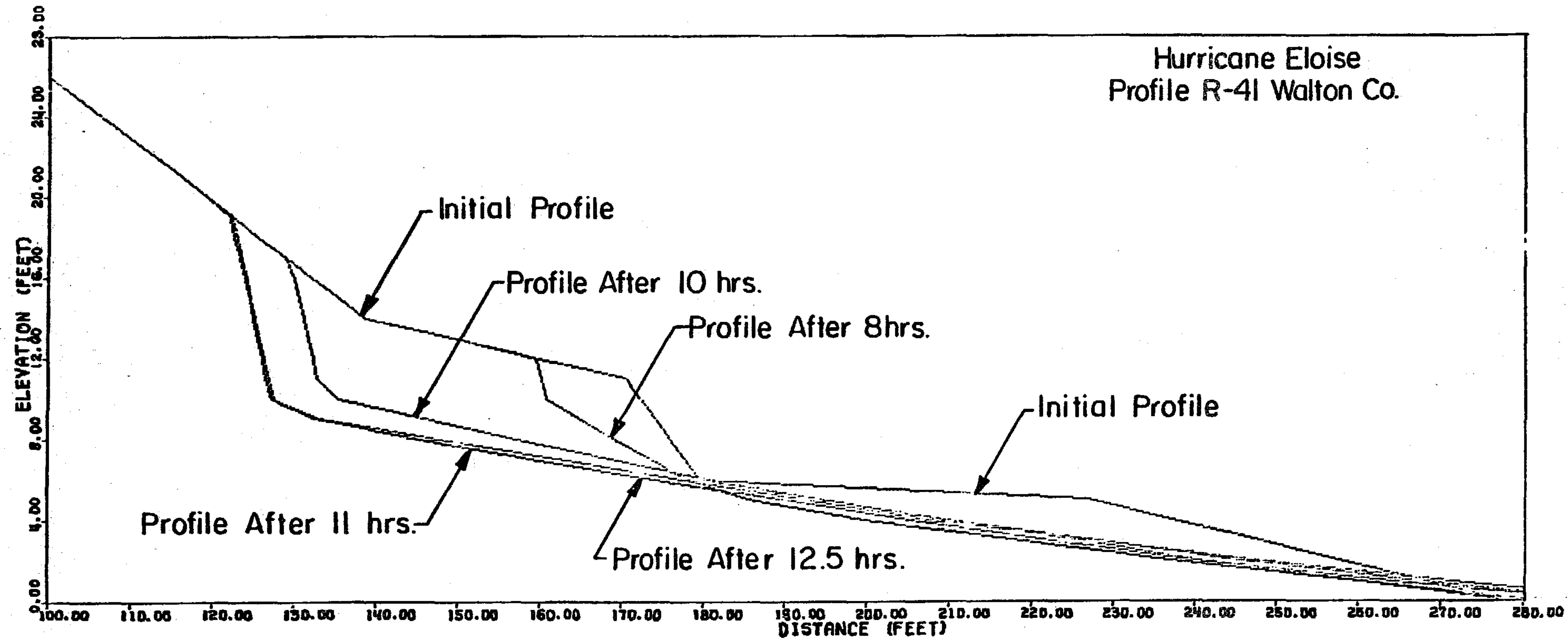
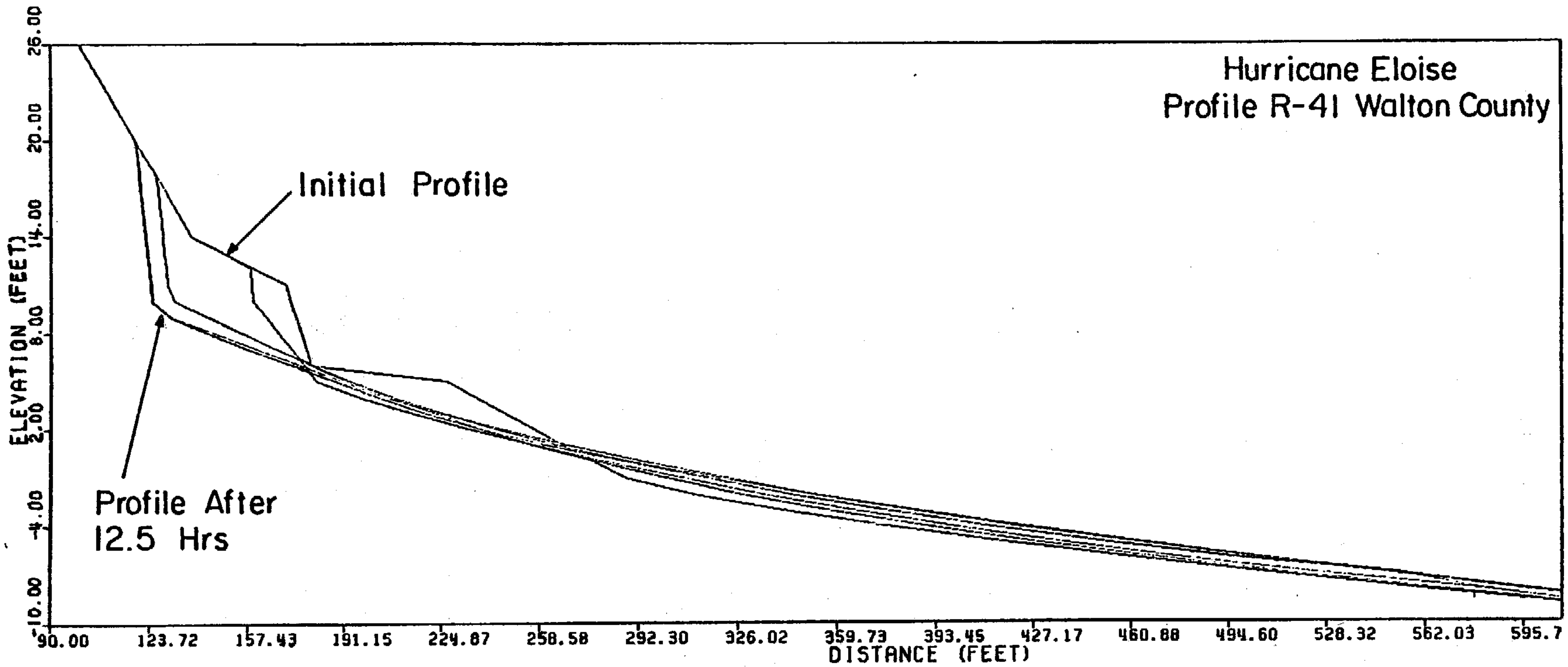


FIGURE 17. EXAMPLE OF OFFSHORE AND NEARSHORE PREDICTED PROFILE FORMS



Verification Using Additional Field Profiles

As noted, numerical simulations are also carried out on an additional 20 profiles from the Hurricane Eloise data set. These profiles are selected to be representative of those profiles showing the maximum erosion either in terms of volume eroded or, in the case of low dunes, in terms of contour recession. The selected profiles cover the entire Walton County shoreline and several groups of closely spaced profiles are chosen to indicate the natural variability that may exist between adjacent profiles. All tests are made with $K = 0.0045$ ft^4/lb as established by calibration tests. Input in each case consists of idealized pre-storm profiles, that is, described by a dune crest position and dune face slope and a berm crest position and beach face slope. Offshore profiles are all simulated initially by $A = 0.184$ $ft^{1/3}$. Breaking depths and offshore slopes are established at 12 feet and 1:15 respectively, as in the case of profile R-41. Storm surge hydrographs are identical in form to Figure 11 but increased by a multiplicative constant suggested by Dean and Chiu for each profile. Other input variables include the observed post-storm dune slope, beach slope, and runup distance as determined for each profile. Estimates of total eroded volumes are obtained from the pre- and post-storm profiles and are subject to uncertainties as discussed previously.

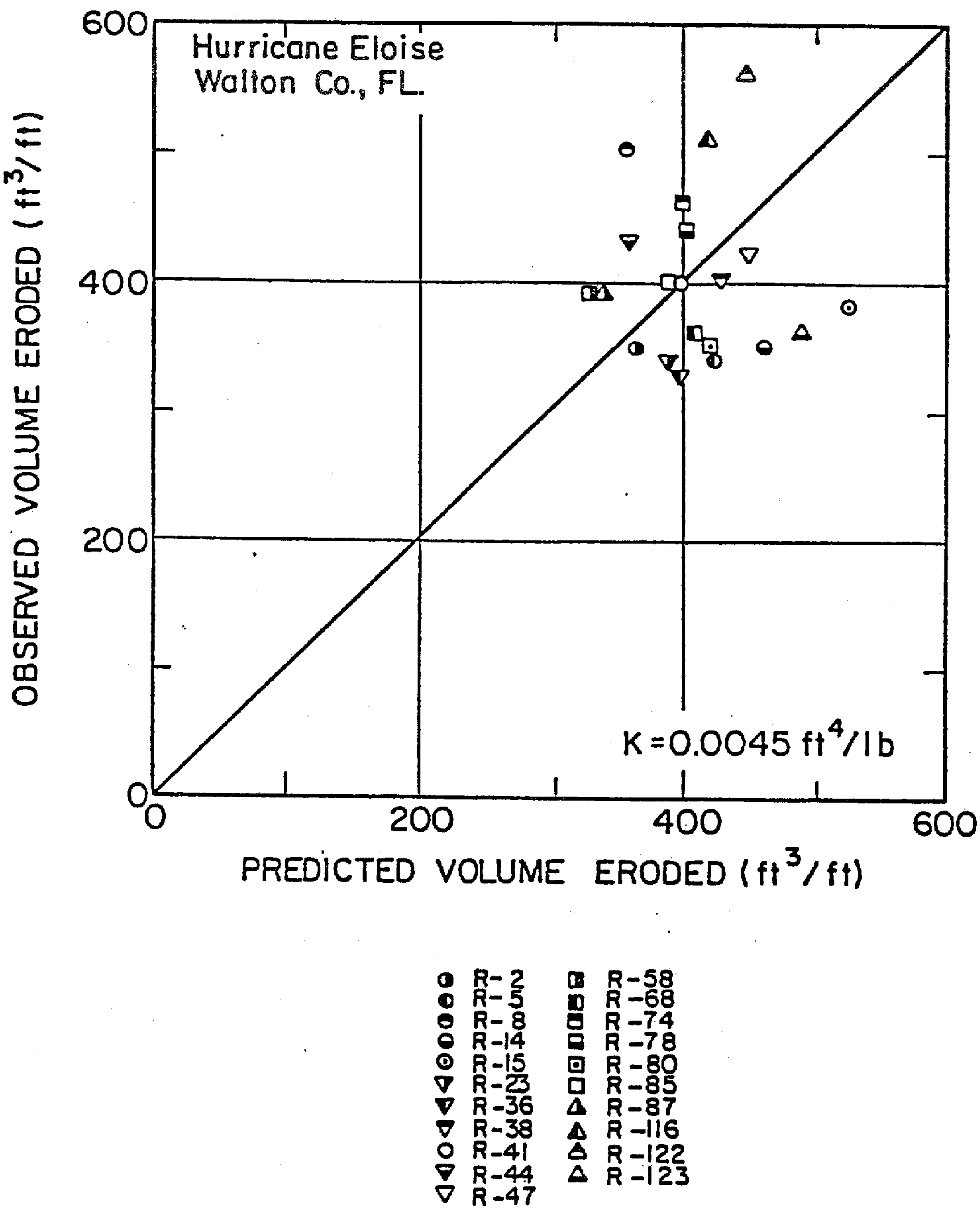
In Figure 18, predicted eroded volumes are compared to observed values for the 20 profiles and for the calibration profile R-41. The diagonal line represents perfect agreement between predicted and observed values and falls through profile R-41. There is considerable scatter in the data points about the line of complete agreement; however, there seems to be little bias as the numerical model overpredicts erosion in 11 cases and underpredicts in 9 cases. In 5 cases, predictions are within 10 percent of the assumed observed values; in 16 cases predictions are within 25 percent of observed values; and all 20 cases are within a 40 percent margin of error.

Errors outside the 25 percent range may be attributed to several factors. For profile R-8, the model underpredicts erosion substantially. However, the large eroded volume at R-8 appears to be a local anomaly; adjacent profile R-9 shows about 300 ft^3/ft of erosion while adjacent profile R-7 shows net accretion. For profiles R-114, R-15, and R-123 the model overpredicts erosion by 30 to 40 percent. The explanation for this seems to be that these are among the steepest profiles simulated and, as discussed by Kriebel (1982), the numerical scheme does tend to predict greater erosion in areas of steep berm or dune slopes. Again, however, local longshore effects may play a considerable role; profile R-122 just 1,000 feet west of R-123, shows the greatest observed erosion of the 21 profiles and is underpredicted by the numerical model by about 25 percent.

Results are somewhat biased in the prediction of dune recession. Of the 20 tests, the location of the dune scarp is correctly predicted on 4 profiles; is slightly overpredicted on 5 profiles and is underpredicted on 11 profiles. On average, the position of the dune scarp was underpredicted by 5.4 feet. Extreme estimates range from an underprediction of 18 feet (out of a total observed recession of about 55 feet for a 33 percent error) to an overestimate of 5 feet (out of a total observed recession of 36 feet for a 14 percent

FIGURE 18

COMPARISON OF PREDICTED TO OBSERVED EROSION
FOR 20 BEACH PROFILES FROM WALTON COUNTY, FLORIDA



error). Based on these results, dune scarp location might be better predicted with a slightly larger K value.

Summary of Calibration-Verification Phase

The modified numerical erosion model seems to be well-calibrated and verified for application to other areas. The first calibration, against Saville's large-scale laboratory profile, provides some indication of the validity of the model for predicting time-dependent profile development, including beach face slope steepening. Saville's tests are quite controlled relative to prototype conditions, yet the best-fit K value, 0.0045 ft^4/lb, should be representative of full-scale (prototype) events.

The second calibration, against profile R-41 from the Hurricane Eloise data set, is less conclusive in terms of precise numerical calibration. However, it also indicates a best-fit K value of approximately 0.0045 ft^4/lb for prototype erosion under severe storm conditions. Certainly, the agreement between this calibration test and the Saville calibration should be viewed, in part, as a fortuitous correlation. This conclusion is supported by the comparison of numerical predictions to observed erosion for an additional 20 profiles from the Hurricane Eloise data set where the best-fit K = 0.0045 ft^4/lb gives agreement to within a 25 percent error on 16 profiles. Larger errors on the other 4 profiles are mainly attributed to localized longshore erosion effects that cannot be accounted for in the model. A further conclusion reached is that beach slope changes and dune scarps are reasonably approximated by the model.

For application to other dune erosion predictions, the following guidelines are recommended:

1) For the modified erosion model, K = 0.0045 ft^4/lb should be used to obtain average dune erosion characteristics.

2) Actual dune erosion is highly variable due to a number of natural factors. Numerical predictions are also sensitive to some parameters such as very steep slope. Therefore, all erosion estimates should be considered average estimates with probable errors of around 25 percent and possible errors 40 percent or more.

3) While individual contour recession predictions are much better than those previously obtained (Kriebel 1982), estimates of dune recession should also be considered average within probable error limits of 5 to 20 feet or 25 percent and perhaps more. The model also is somewhat biased, however, and tends to underpredict dune recession based on the profiles tested.

SECTION IV

APPLICATION TO OCEAN CITY, MARYLAND -- STORM EROSION

Background

The numerical erosion model is applied to Ocean City, Maryland, to obtain estimates of the storm erosion potential of existing beach profile forms. With the calibration and verification of the model, it is expected that the time-dependent erosion due to severe storms at Ocean City may be estimated to within the same level of accuracy obtained in the hindcast of erosion associated with Hurricane Eloise.

In this study, a typical or representative profile form, similar to that suggested by Everts (1984), is adopted. The shoreface and backshore are taken from the 55th Street profile which is described as "typical" by the U.S. Army Corps of Engineers (1980). This profile is characterized by a low, broad dune with a crest elevation of +14 feet NGVD (National Geodetic Vertical Datum), a linear dune face with a 1:10 slope, and a 40-foot wide berm at +5 to +6 feet NGVD. The beach slope is taken to be 1:10 as given by the Corps of Engineers and Trident Engineering (1979). The set of Ocean City beach profiles provided by Leatherman (1984b) indicate that average dune heights vary between about 8 and 15 feet NGVD. Therefore, numerical simulations are also performed on beach profiles with crest elevations of 10 and 12 feet in addition to the reference profile, with a 14-foot crest elevation. The range of dune configurations tested is depicted in Figure 19.

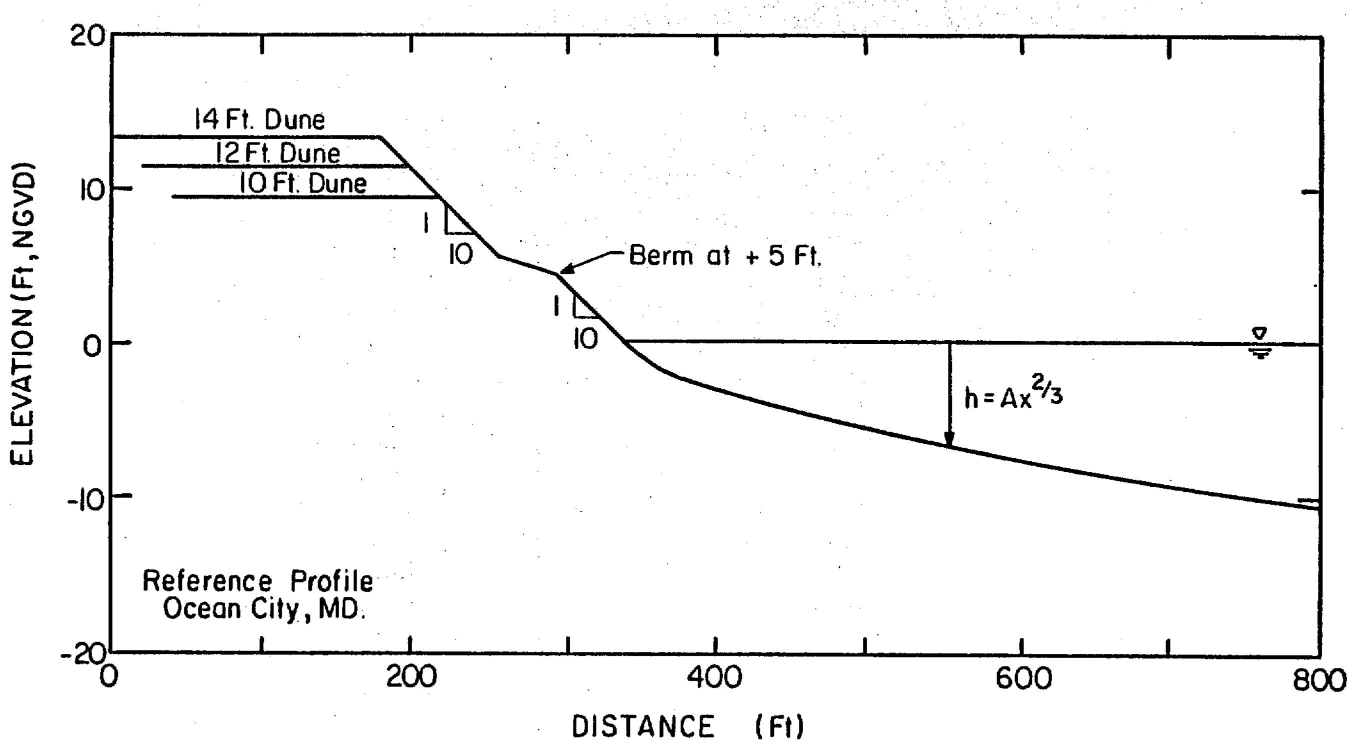
The offshore regions of Ocean City beach profiles are highly variable as suggested by the overlays of the 1929, 1965, 1978, and 1979 profiles provided by Leatherman (1984b). General profile characteristics include a fairly mild slope to depths of -7 feet followed by steeper slopes to -15 to -20 feet contours, after which the profiles flatten considerably. The apparent steepening below -7 foot depths is a subject of some interest. It appears that over the past several decades this portion of the profile has steepened considerably while the nearshore zone, i.e., above -7 foot contour, has remained fairly stable.

In this study, two scenarios for the observed profile forms are investigated in which: 1) the existing profile is considered to be in approximate equilibrium and 2) the existing profile is considered to be artificially steepening away from a more gently sloping equilibrium profiles form. For each scenario, the equilibrium form of the profile is approximated by a monotonic profile of the $Ax^{2/3}$ form.

For the equilibrium scenario, the average profile of Everts and the profiles provided by Leatherman have been analyzed, and approximate best-fit A values are obtained between the shoreline and an assumed closure depth of 28 ft. For the 1979 profile, an A value of about 0.250 $ft^{1/3}$ seems to provide the best fit; however, 1965 and 1978 profiles suggest an A value of about 0.200 $ft^{1/3}$. Due to the significant variation between the 1978 and 1979 profiles and the close agreement between 1965 and 1978 profiles, the 1979

FIGURE 19

NEARSHORE BEACH PROFILE, OCEAN CITY, MARYLAND



profiles have been disregarded and the representative A value of 0.200 $ft^{1/3}$ is adopted. The monotonic $Ax^{2/3}$ curve obtained using A = 0.200 $ft^{1/3}$ typically overpredicts depths nearshore and slightly underpredicts depths offshore, but represents approximately the total volume of sand in the profile.

For the second scenario, in which the existing profile is assumed to be steeper than a representative $Ax^{2/3}$ equilibrium form, separate analyses indicate that A = 0.175 $ft^{1/3}$ provides a reasonable equilibrium approximation. Based on the median sand grain diameter, given by the U.S. Army Corps of Engineers (1980) as 2.02ϕ, or 0.24 mm, the corresponding A value from Figure 2 is about 0.180 $ft^{1/3}$. Likewise when an $Ax^{1/3}$ form is fitted through the nearshore portion of the profiles provided by Leatherman, best-fit A values seem to range from about 0.150 to 0.200 $ft^{1/3}$ with most common values of about 0.175 $ft^{1/3}$. Based on these two inconclusive, but supporting sources, an A value of 0.175 $ft^{1/3}$ is adopted as being representative of an equilibrium profile form that is milder than most observed profiles.

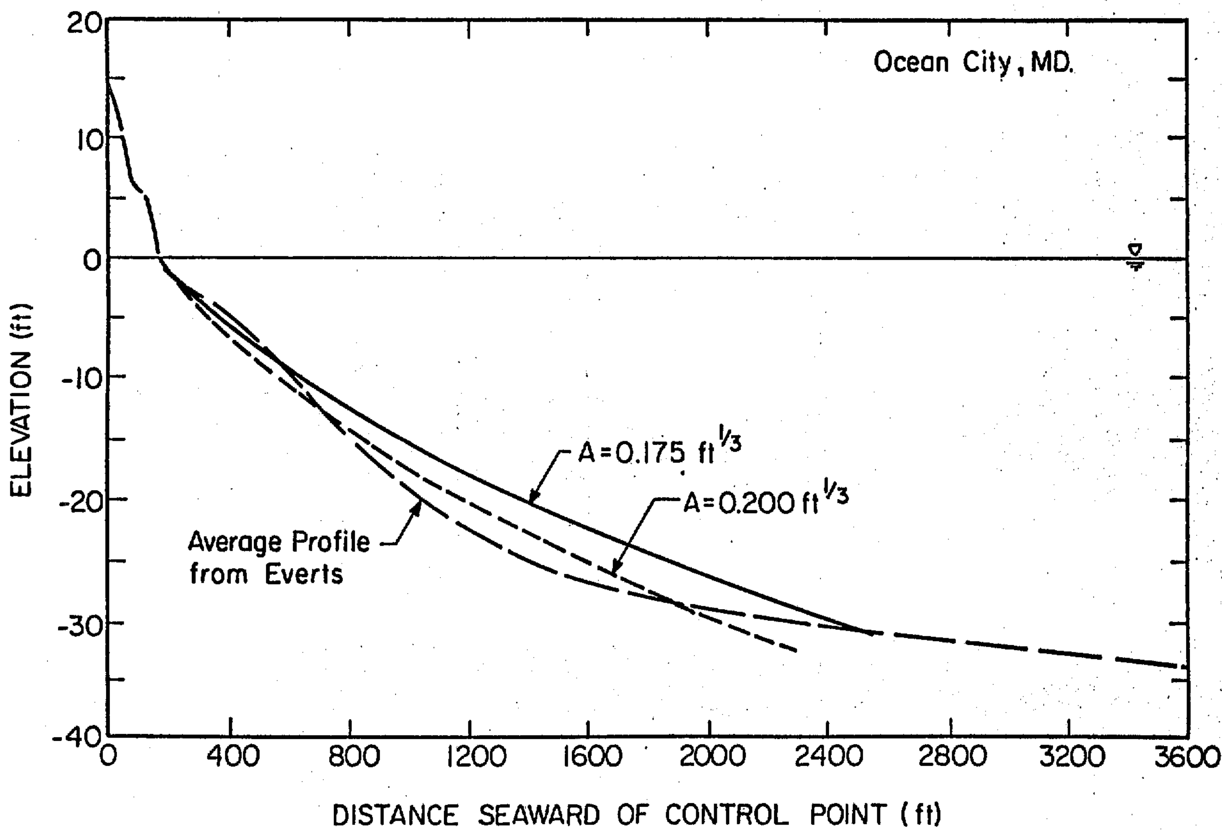
It should be noted that A = 0.175 $ft^{1/3}$ does provide a better overall fit to profiles S-65, S-48, and S-3 than A = 0.200 $ft^{1/3}$. On the remainder of the profiles, A = 0.175 $ft^{1/3}$ provides a good fit nearshore to depths of -7 to -10 feet, then predicts milder slopes than are observed. In effect, if A = 0.175 $ft^{1/3}$ is a reasonable approximation of the equilibrium form, a large sand deficit exists offshore which must be filled by shifting sand from the beach face. It appears that this readjustment is being prevented or delayed in the active surf zone, i.e. out to depths of about -7 feet, perhaps by the presence of shoreline stabilization structures.

In Figure 20, the two proposed equilibrium profile forms are shown along with the average profile used by Everts. For subsequent analysis, the storm erosion potential is determined for each profile form but it is expected that, since storms affect the upper portion of the profile, the results for the milder profile, A = 0.175 $ft^{1/3}$, will be most realistic. The erosion potential for profile adjustment to equilibrium and sea level rise is also considered for either scenario and results may be interpreted as providing a range of estimates only, as the appropriate equilibrium form for long-term profile development is unknown.

In order to develop storm erosion probabilities, storm surge elevations corresponding to 10-, 40-, 100-, and 500-year return periods are used. These values provide four data points with approximately equal spacing on a log-normal plot of storm erosion magnitudes so that erosion associated with other return periods may be easily interpolated. Based on the National Weather Service (Ho et al. 1976) joint storm tide analysis, the combined probabilities of hurricanes and winter storms are represented by a single frequency curve. In general, hurricanes may be considered the most severe storms in terms of peak storm surge elevations. Therefore, hurricanes dominate the higher, 100- to 500-year, return periods, while winter storms are predominant at lower, 10- to 50-year, return periods. The National Weather Service predictions, adopted by the U.S. Army Corps of Engineers (1980), are used in this study, and appropriate peak storm tide elevations for the four return periods tested are given as:

FIGURE 20

APPROXIMATE EQUILIBRIUM OFFSHORE PROFILE FORMS
Ocean City, Maryland



Return Periods	Frequency Per Year	Peak Surge (ft)
10	0.1	6.3
40	0.025	7.5
100	0.01	8.7
500	0.002	10.3

Since the time-characteristics of the storm surge have a major influence on the extent of erosion during a severe storm, it is also necessary to evaluate the effects of various surge durations. For this purpose, the storm surge hydrograph is approximated by a sine-squared distribution as

$$S(t) = S_p \sin^2(\pi t/T)$$

where S(t) is the surge level at time t, S_p is the peak surge level, and T is the total storm surge duration defined as the time between departure from a no-surge condition and return to the same condition.

In this study, three surge durations, T, are evaluated. For typical hurricanes, a 24-hour total duration is assumed due to the general fast motion of hurricanes in an alongshore direction at Ocean City. For typical winter storms, a 48-hour total duration is assumed, based on the surge hydrograph for the 1956 storm presented by the National Weather Service (Ho et al. 1976). Finally, since at least two winter storms have had total durations of at least 4 days, a duration of 96 hours is also evaluated. This surge duration corresponds to the March 1962 storm, generally the most destructive storm experienced along the U.S. East Coast in recent times. Based on an estimated peak surge elevation of 7.8 feet NGVD at Ocean City, the March 1962 storm surge elevations are expected to be equalled or exceeded about once in 50 years. Due to the unusually long duration of this storm, the actual probability of reoccurrence is probably much less than 0.02; however, without statistical description of joint storm surge/duration probabilities, it is difficult to estimate the probability more precisely. In any event, the fact that such a severe storm did occur in 1962 is sufficient reason for many planners and engineers to consider its reoccurrence.

Other required input data include an estimate of the runup limit and an estimate of storm breaking wave heights that effectively limit offshore sediment transport. Based on the results of Hurricane Eloise simulations, an approximate location of the break between the dune scarp and the beach face is about 2-3 feet above the peak surge level for cases with tall dunes and slightly higher for low dunes when swash may overtop the dune. For Ocean City, where dune crests are low, an effective runup of 4 feet is assumed. For an estimate of the breaking wave heights, wave data given by Bretschneider (1964) for the March 1962 storm at Bethany Beach, Delaware, are used. In that storm, wave heights in 17 feet of water increased rapidly to 10 to 12 feet and were maintained at that level throughout most of the storm. As noted, estimates of erosion during Hurricane Eloise based on variable wave heights were about 5 percent lower than estimates based on a constant wave height. Since model calibration is based on a constant wave height, however, a constant breaking wave height of 10 feet is used to estimate storm erosion for Ocean City.

Erosion Estimates

Estimates of storm-induced erosion are obtained for 72 cases covering the range of profile forms, storm surge elevations, and storm durations of interest. As a brief summary, the simulated conditions correspond to all possible permutations associated with the following input variables:

Variable	Units	Values Tested
A parameter	$ft^{1/3}$	0.175, 0.200
Dune Elevations	ft	10, 12, 14
Peak Storm Surge Elevations	ft	6.3, 7.5, 8.7, 10.3
Storm Durations	hours	24, 48, 96

Output from the erosion model in each of the 72 cases includes the post-storm profile at the time of maximum erosion, the total volume of sand eroded above the 0-ft contour, and the recession of the dune crest. Numerical results for the volume eroded and dune recession are presented in Figures 21 through 23 where each set of figures corresponds to a given dune configuration. Primary discussion in this study is directed toward results obtained for the reference profile, in Figure 21, with a dune height of 14 feet. Other results are discussed briefly to indicate the range of erosion predictions that might be expected over the Ocean City coastline where dune heights differ from the reference profile.

As a guide to interpretation of Figures 21 through 23, the six curves in each figure represent a given set of storm duration and profile conditions for the range of peak surge levels tested. Smooth curves have been drawn through the four data points obtained from the four peak surge levels to aid interpolation of erosion estimates for other surge levels. Of the six curves in each figure, the three solid curves correspond to erosion predictions for $A = 0.175\ ft^{1/3}$ and the three storm durations of 96, 48, and 24 hours; the three dashed curves represent erosion estimates for $A = 0.200\ ft^{1/3}$ for the three storm durations.

The curves are plotted with respect to the return periods for the four peak surge elevations but do not represent the probability of erosion associated with given return periods. Instead, for a given peak surge elevation and return period, there is a distribution of expected erosion events corresponding to the distribution of expected storm durations. If the distribution of storm durations were known, such that the probabilities of 24-, 48-, or 96-hour storm durations could be determined, then the total erosion frequency distribution could be obtained by considering the joint probabilities of storm surge and storm duration. Due to the limited scope of this study, the three erosion estimates are given for each storm surge return period to indicate the range of erosion that may be expected for storms with a given magnitude, or peak surge level.

Erosion estimates, in Figures 21 through 23, vary in a predictable fashion according to storm surge characteristics and assumed dune crest heights. Based on the reference profile, erosion estimates for the shortest storm duration range from 469 to 741 cubic feet of sand per linear foot of shoreline

FIGURE 21

STORM EROSION ESTIMATES, 14-FOOT DUNE HEIGHT

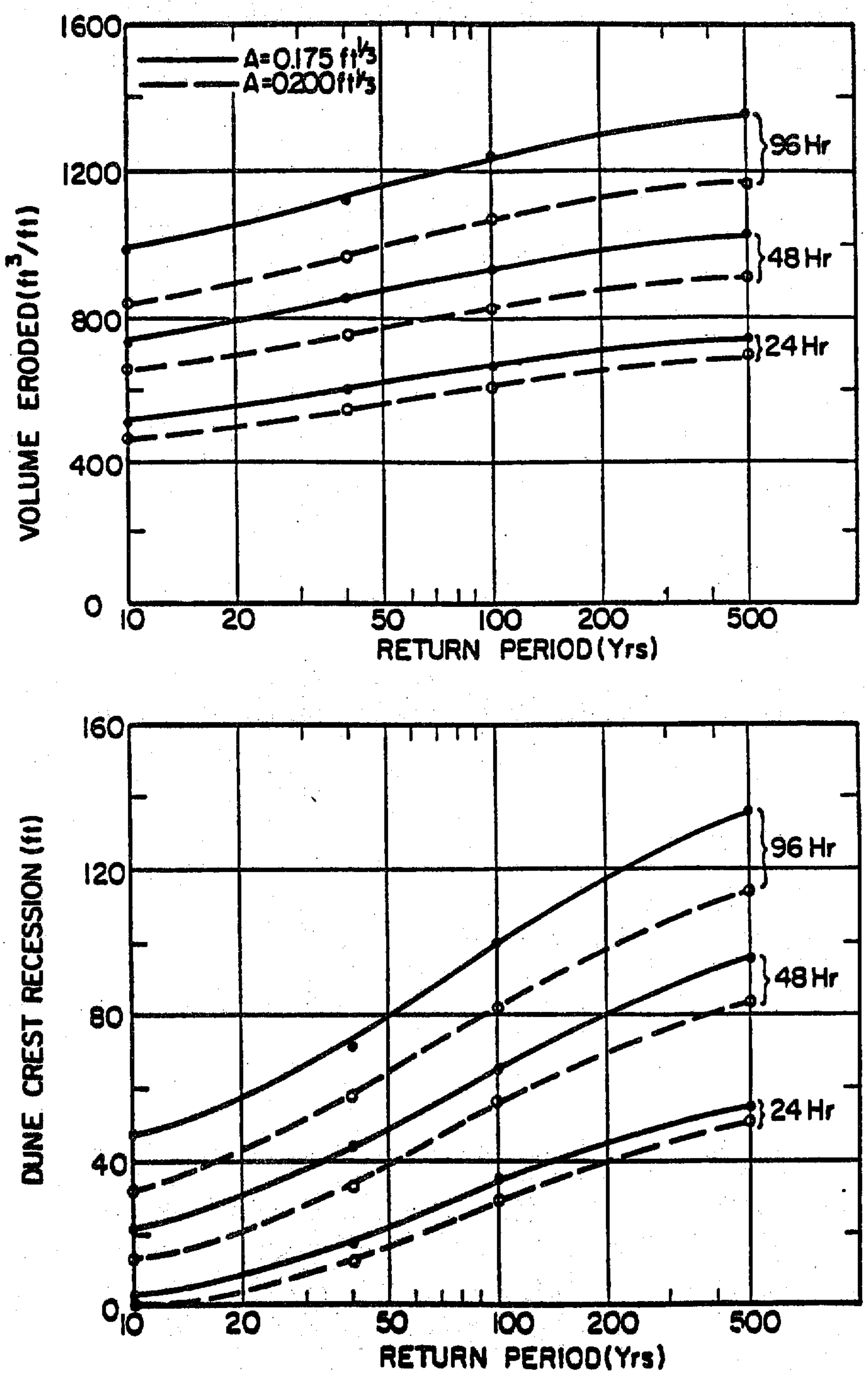
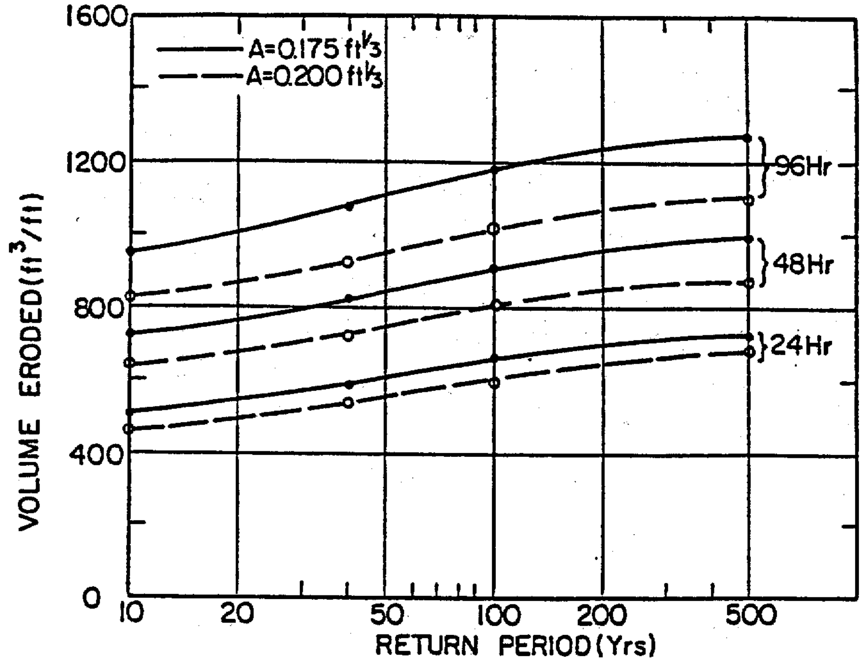


FIGURE 22

STORM EROSION ESTIMATES, 12 FOOT DUNE HEIGHT



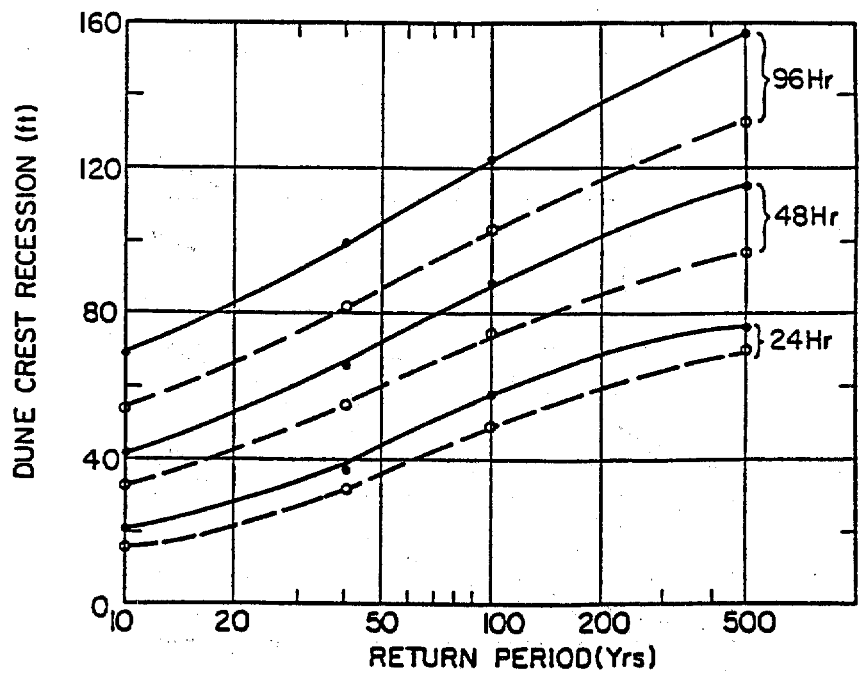
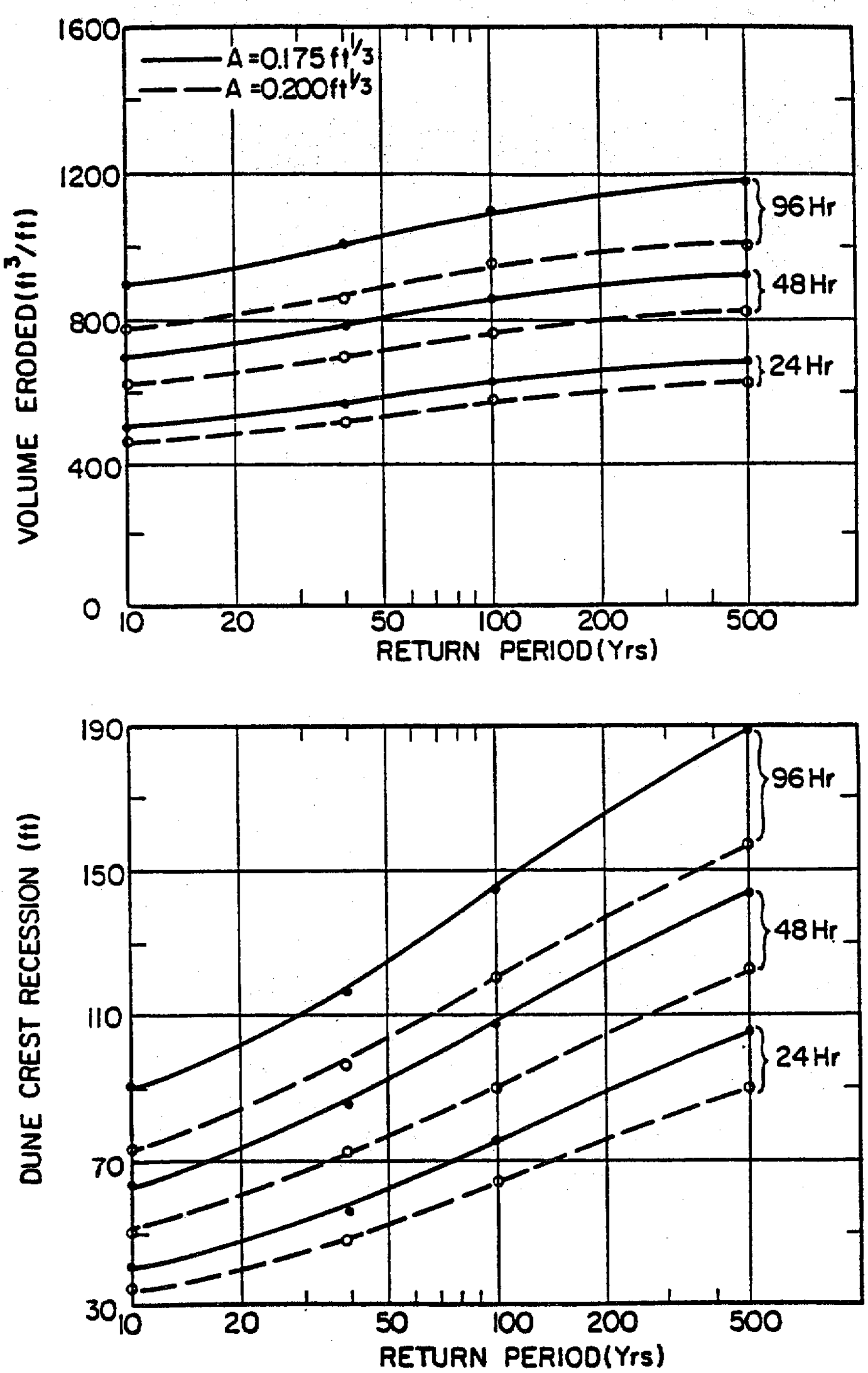


FIGURE 23

STORM EROSION ESTIMATES, 10-FOOT DUNE HEIGHT



(ft^3/ft) with corresponding dune recession of 0 to 53 feet. Erosion estimates for the longest storm duration, comparable to the March 1962 storm, range from 770 to 1361 ft^3/ft with dune recession of 32 to 189 feet. Best estimates for erosion values that might be expected for a repeat of the March 1962 storm, that is, a 7.5-ft peak surge for a 96-hour storm duration, are volumetric erosion of 974 to 1129 ft^3/ft and a recession of 58 to 71 feet for the 14-foot dune crest.

In Figures 24 through 27, estimated post-storm profiles are shown for the four peak storm surge levels and the three durations tested. Results are for an A value of 0.175 $ft^{1/3}$ and for the reference profile with dune height of 14 feet. Erosion estimates for the reference profile vary from 516 to 1361 ft^3/ft of erosion with dune recession of 2 to 136 feet.

Although field data are not available to conclusively verify these erosion estimates, predicted values appear reasonable when compared to observations from storms of record. Bretschneider (1964) presents estimated beach profiles for the Delaware coast before and after the March 1962 storm where dune recession of 50 to 100 feet occurred. Hayes (1967) has also documented average dune recession of 100 feet on central Padre Island, Texas, after Hurricane Carla, which had a duration of more than 80 hours. Vellinga (1983b) presents field measurements of erosion in the Netherlands in which volumes of up to 1600 ft^3/ft (up to 150 m^3/m) were eroded along with 30 to 70 feet of dune recession. Finally, the Shore Protection Manual (U.S. Army Corps of Engineers 1977) suggests the following guidelines for storm related erosion:

Storm Class	Volume Eroded (ft^3/ft)
Moderate	108 - 270
Extreme (or moderate that persists for long duration)	270 - 540
Rare	540 - 1350

While quantification of the above storm classes is not available, and would vary with location, all storms tested in this study have long durations typical of the most severe storms of record and fall easily within the Extreme to Rare classifications. Based on this brief and inconclusive comparison, it does appear that numerical estimates are of the correct order-of-magnitude; and, based on descriptions of historical storms, estimates seem as likely to underestimate as to overestimate erosion. Since this finding is also substantiated by application of the numerical model to the Hurricane Eloise field data set, the numerical estimates for storm erosion at Ocean City are considered to be subject to the same ±25 percent probable errors found during the verification phase of this study.

In Figures 21 through 23 the erosion estimates for A = 0.175 $ft^{1/3}$ and A = 0.200 $ft^{1/3}$ are offset almost linearly for each storm duration, with A = 175 $ft^{1/3}$ always giving the larger erosion magnitudes. Results for the two A values agree very closely for the 24-hour storm duration estimates and eroded volume differs by less than 20 percent for 96-hour storm durations. While these two A values may provide high- and low-range erosion estimates,

FIGURE 24

ESTIMATED POST-STORM EROSION PROFILES, 6.3-FOOT PEAK STORM SURGE

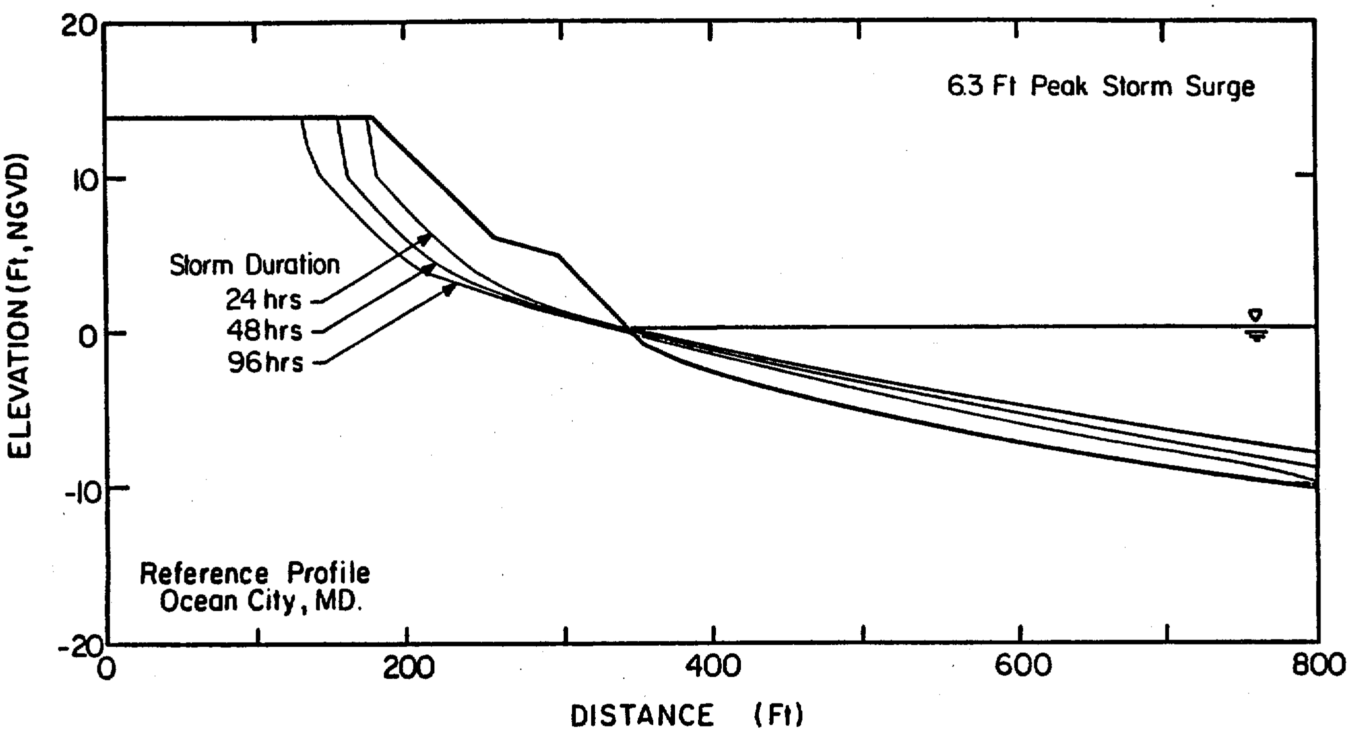


FIGURE 25

ESTIMATED POST-STORM EROSION PROFILES,
7.5-FOOT PEAK STORM SURGE

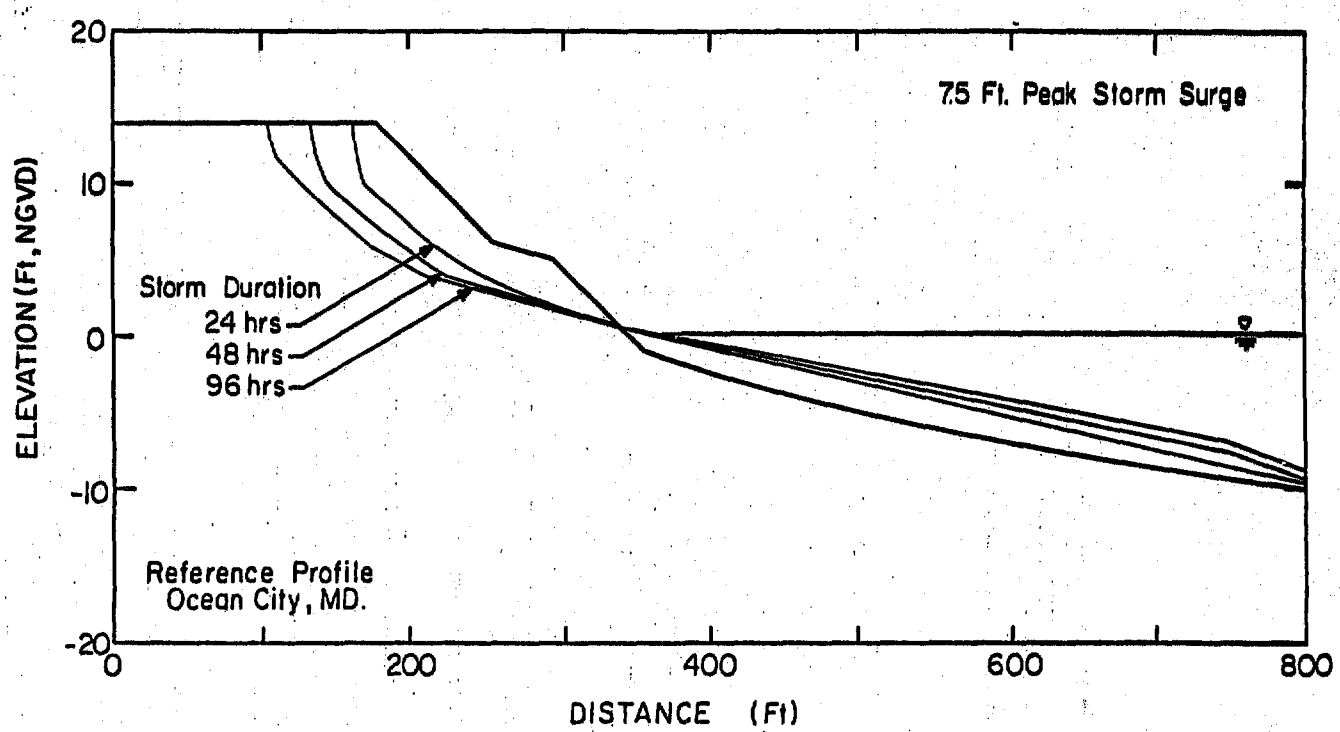


FIGURE 26

ESTIMATED POST-STORM EROSION PROFILES,
8.7-FOOT PEAK STORM SURGE

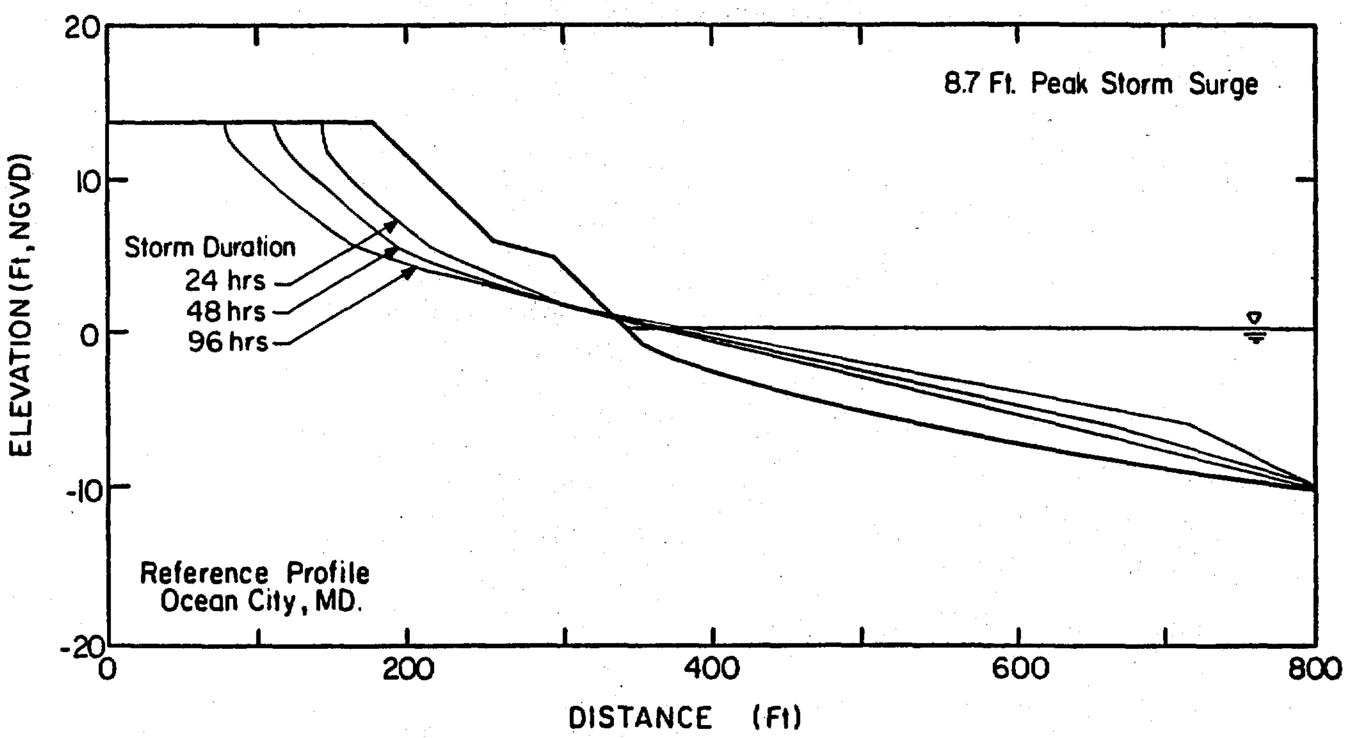
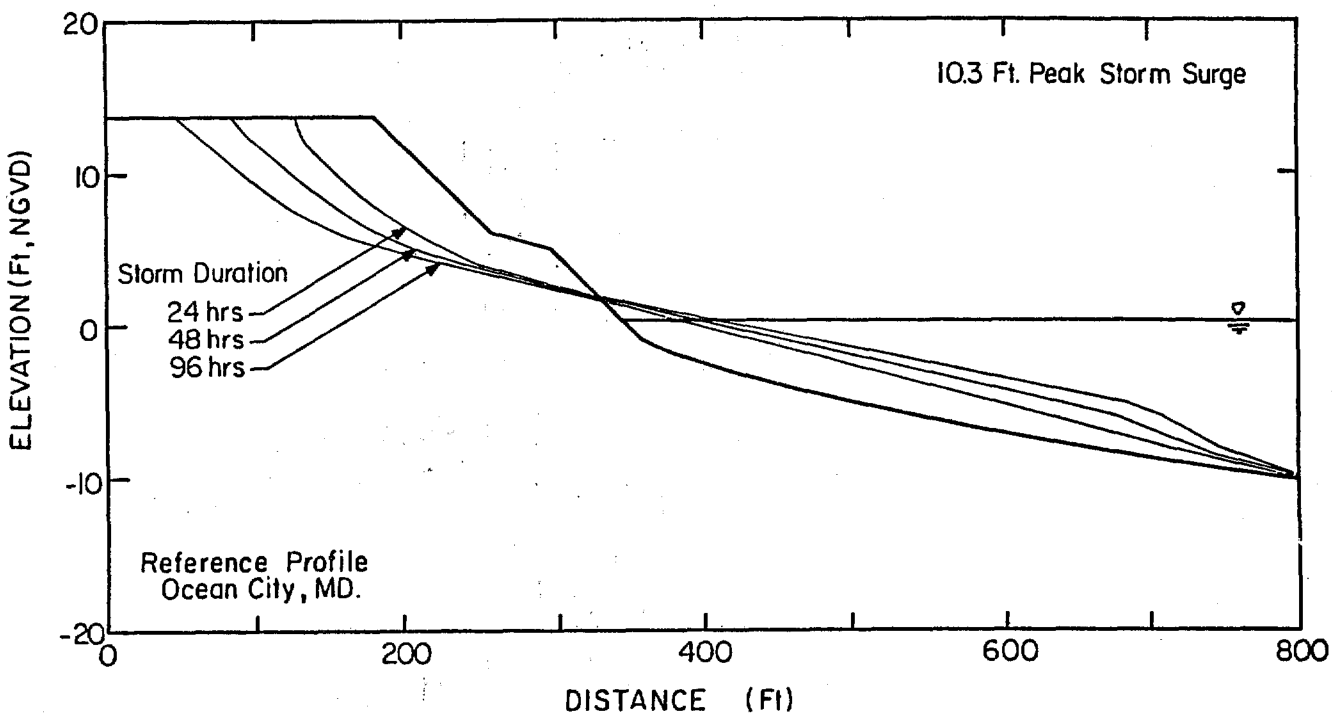


FIGURE 27

ESTIMATED POST-STORM EROSION PROFILES, 10.3-FOOT PEAK STORM SURGE



the results for $A = 0.175\ ft^{1/3}$ are considered the most realistic for estimating storm erosion magnitudes. This conclusion is based on the comparisons of the two monotonic $Ax^{2/3}$ profile forms to the Ocean City beach profiles, where $A = 0.175\ ft^{1/3}$ provides the best fit for nearshore portions of the profile that are dominated by normal wave activity.

Storm surge elevation and duration are both found to be important parameters in determining the storm erosion potential. When considering the volume of sand eroded, variations in storm duration are of greater importance than variations in storm surge elevation over the range of values tested. However, dune recession seems to be almost equally influenced by storm duration and magnitude. These conclusions emphasize the need to consider the joint probability of occurrence of storm duration for a given storm surge magnitude when estimating storm erosion potential.

Numerical results for different dune height scenarios, in Figures 21 through 23, exhibit expected results where smaller dunes erode farther but with less total volume eroded. Reductions in dune height from 14 to 10 feet cause a decrease in eroded volume of about 10 to 15 percent while leading to increases in dune recession of over 50 percent for the most extreme storm durations tested, with absolute increases in dune recession of 45 to 50 feet for all scenarios considered. These results have rather important implications for erosion mitigation. Protective dunes that are high and narrow must store a greater sand volume than low, broad dunes. However, the benefit in reduction of sand volume achieved by construction of wide berms or dunes must be weighed against the potential for overwash and flooding that may be more effectively controlled by high dunes.

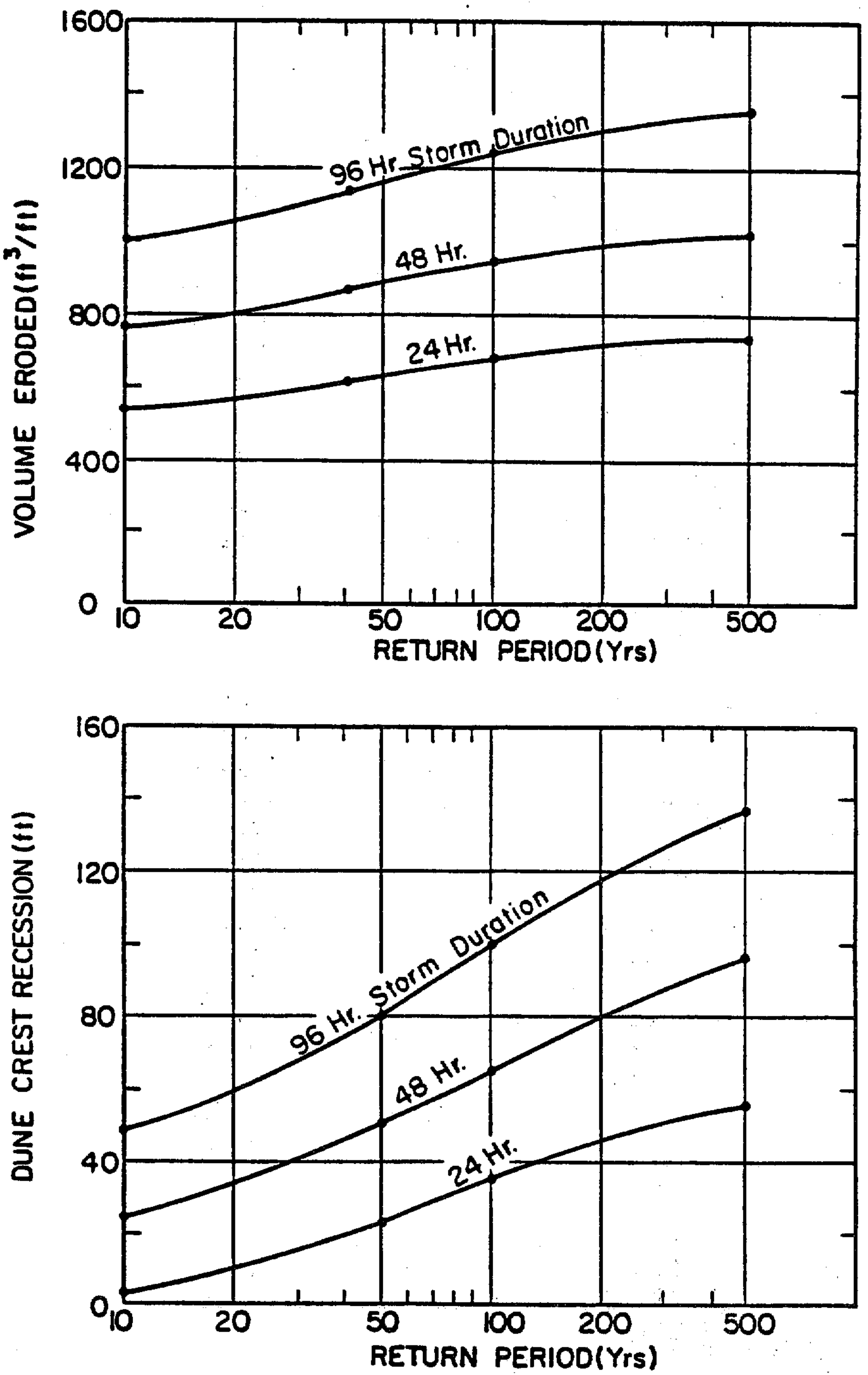
It is emphasized that effects of dune breaching and overwash are not simulated in the numerical model. The 10-foot dune will certainly be overtopped by the 100- to 500-year storms and overtopping may occur with other dune heights as well. Likewise, since dunes at Ocean City are narrow, numerical estimates indicate that complete erosion of existing dunes may occur under several storm scenarios. Numerical results assume a uniform profile landward of the dune crest and do not consider structures that may be present. For cases where these assumptions are not valid, numerical results indicate the erosion potential that exists and may be used to identify areas in which dune breaching, overwash, or structural undermining is expected. For example, a typical cross-section of the Ocean City area shows that elevations decrease to nearly +8 feet about 200 feet landward of the dune crest. From Figures 24 through 27, severe overwash and flooding can be expected for the 10.5-foot storm surge of all durations while the 6.5-foot storm surge seems likely to result in significant overwash for the 96-hour duration storm only.

Summary of Storm Erosion Calculations

Erosion estimates adopted for the reference profile are summarized in Figure 28 for the range of storm conditions tested. Guidelines for use of these estimates are summarized as follows:

FIGURE 28

ADOPTED STORM EROSION ESTIMATES FOR
REFERENCE PROFILE, OCEAN CITY, MARYLAND



(1) Storm erosion estimates are based on the modified Kriebel and Dean numerical erosion model. The model has been calibrated and verified, and is considered to be accurate to within probable errors of ± 25 percent and possible errors of ± 50 percent.

2) The erosion estimates do not account for longshore sediment transport gradients during a severe storm; however, based on estimates of the effect of oblique waves by Swart (1974) and Vellinga (1983b) it is believed that most longshore effects may be accounted for by applying the error margins listed above.

3) The erosion estimates do not account for the presence of structures and assume that the eroding dune is able to supply sand freely to the active profile. The influence of shore stabilization structures (i.e., groins, seawalls, or revetments) cannot be tested; likewise, the effect of residential or commercial structures or paved roads cannot be determined.

4) The erosion estimates do not consider overwash processes that may move a considerable sand volume over the dune crest or through breaches in the dune line. For high dune scenarios, this may not be a critical omission; however, for low dunes, overwash is known to be an important process. In numerical calculations, if the storm surge elevation exceeds the dune crest elevation, as it may for the 10-ft dune scenario, the limit of active sediment transport is established at the dune crest. In these cases, large offshore sediment transport rates occur seaward of the dune crest while no sediment transport is assumed landward of the dune crest. This creates a large sand deficit at the dune crest which erodes the dune crest and adjacent contours rapidly, thus planing off the profile and giving large dune recession predictions. However, no sand losses in a landward direction are included; therefore, erosion estimates for low dune scenarios may substantially underpredict the horizontal extent of the active profile.

Mitigation Requirements - Storm Erosion

Mitigation requirements are estimated for the reference profile based on the storm erosion estimates presented in Figure 28 and a simple sensitivity analysis. In this analysis, beach fill requirements are estimated as the net volume of sand that must be added above mean sea level in order to prevent recession of the dune crest. Other mitigation requirements may exist, such as the elimination of flooding or overwash; however, it is assumed here that the interest is to prevent erosion of the dune crest.

Beach fill designs typically specify placement of sand in the form of an elevated berm with a linear beach face and a slope near the existing natural slope. It is well known that waves will tend to reshape the fill slope, such that some material is deposited offshore and an apparent erosion of the berm crest occurs. Based on energy dissipation arguments, the fill slope should achieve a general concave form which will then be in dynamic equilibrium with respect to the normal wave climate. During this reshaping process some sand is "lost" from the exposed portions of the beach face; thus, the net volume of sand added to the berm or dune is less than that which is actually placed. Other losses may also occur due to the incompatibility of fill material or due to longshore transport out of the fill area. These effects are not considered in this analysis.

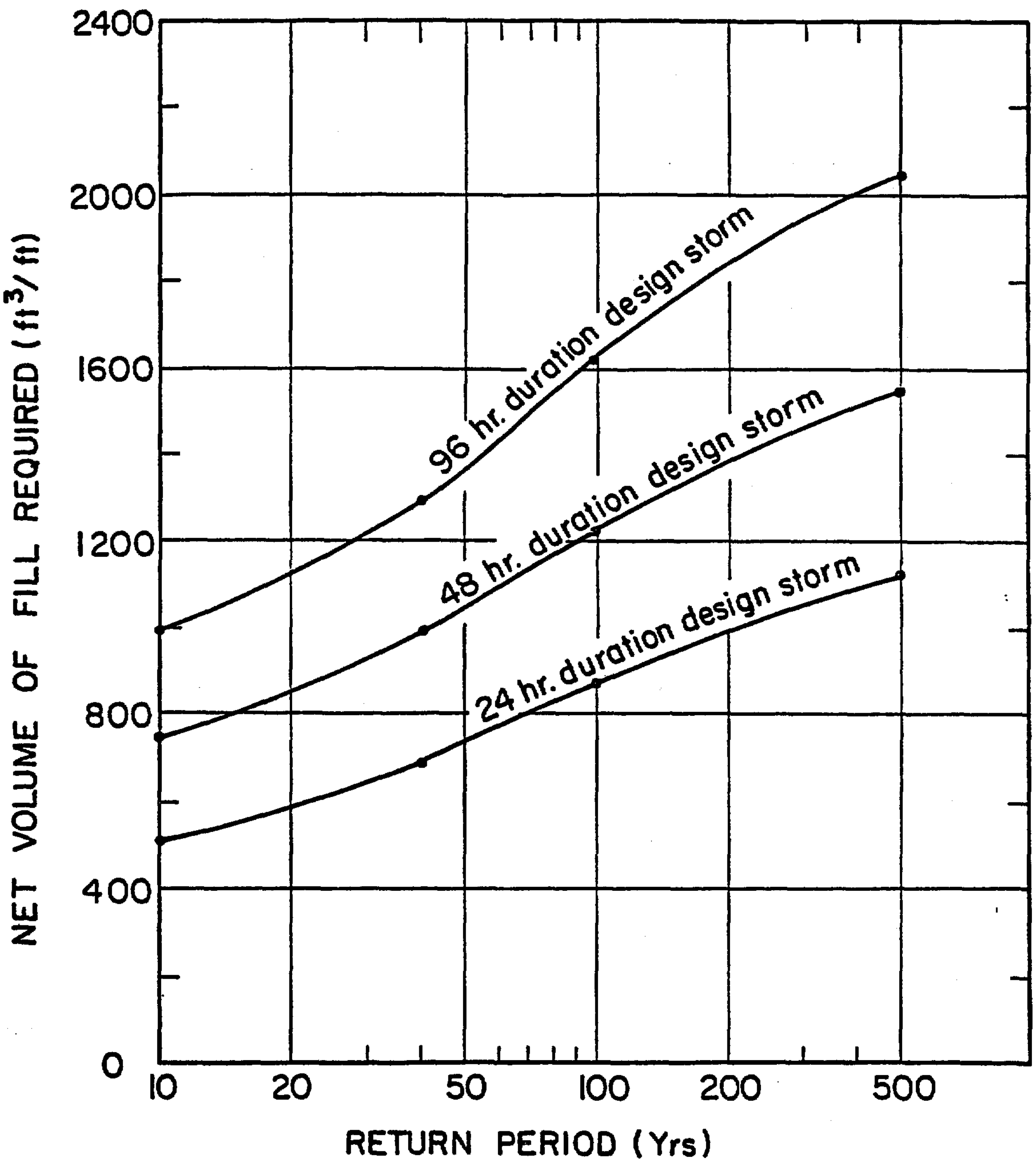
For storm erosion protection, it is the net sand volume remaining above mean sea level after adjusting to equilibrium, that provides additional storm erosion protection. The shape of the fill also may have some impact on the effectiveness of the fill in preventing recession of the dune crest. In this study, the general fill requirements are developed independent of initial fill configuration; specific fill designs should be tested individually to estimate their effectiveness.

A total of eight beach fill schemes are analyzed to estimate basic fill requirements. These schemes include the design recommended by the U.S. Army Corps of Engineers (1980), where a 100-foot wide berm is constructed at +9 feet NGVD to establish a 200-foot wide beach between the dune slope and the mean water line. The other seven schemes are selected somewhat arbitrarily and include designs for a wide natural berm at +5 feet, a wide storm berm at +9 feet, as well as an addition of sand to the dune face. In each case, the volume of sand added to the reference profile is allowed to remold to equilibrium out to a 10-foot depth, after which storm conditions are applied. A combination of the 24-, 48-, and 96-hour storm surges are applied, with peak surge elevations of 6.3, 8.7 and 10.3 feet. Results for each run consist of the erosion characteristics of the 14-foot dune crest.

Guidelines for mitigation are developed by correlating the net sand volume added above mean sea level after equilibrium is attained to the erosion potential of the storm on the reference profile without mitigation. In general, of relatively small water level variations, the net volume of sand that should be added to the beach face (after remolding to equilibrium) should be equal to or greater than the volume of sand that is expected to be eroded from the profile without mitigation. For the storm and profile conditions tested, this seems to apply for all storm durations for peak water levels of up to 6.5 feet. For higher peak surge levels, wave uprush reaches higher on the profile and recession of the upper elevations is more pronounced. For the 8.7-foot peak surge, the net volume of sand added to the beach face should be at least 30 percent greater than the volume that is expected to be eroded without mitigation. For the largest peak surge levels, the net volume added should be about 50 to 60 percent greater than the expected eroded volume without mitigation. Suggested net fill volumes required to provide protection for the reference profile for the range of storm conditions considered are determined as in Figure 29.

FIGURE 29

NET BEACH FILL REQUIREMENTS TO PREVENT DUNE RECESSION FOR REFERENCE PROFILE, OCEAN CITY, MARYLAND



According to numerical estimates, the beach nourishment design recommended by the U.S. Army Corps of Engineers (1980) seems to provide adequate storm erosion protection for the 10-year storm surge with all possible durations and the 100-year storm surge for 24-hour durations. For more intense or longer duration storms, some erosion of the original dune crest, at +14 feet, is expected. The recommended beach fill initially adds about 1450 ft^3/ft to the profile below the +9-ft NGVD elevation. After remolding to equilibrium about 930 ft^3/ft remains above the still water level to provide protection from storm erosion. For the 6.3-ft peak surge, the dune crest does not recede for 24- to 48-hour storm surge levels and recedes 4 feet for the 96-hour storm as shown in Table 1. For the design storm, with 8.7-ft peak surge, the 24-hour storm causes minor dune recession of 5 feet, while the 48-hour and 96-hour storms cause erosion of 27 and 57 feet, respectively. Dune erosion for the 10.3-ft peak surge ranges varies from 35 to 52 to 93 feet for the 24-, 48-, and 96-hour storms, respectively.

Based on guidelines for beach fill volumes in Figure 29, complete protection is provided by the <u>net</u> addition above the still water level of 1000 ft^3/ft for the 10-year storm, 1600 ft^3/ft for the 100-year storm, and 2050 ft^3/ft for the 500-year storm. However, for practical application, where the probability of a 96-hour duration storm may be small, the Corps' design does seem to provide reasonable protection from typical duration storms for the 100-year surge level. The initial fill design and equilibrium fill configuration are shown in Figure 30. Estimated eroded profiles for the 8.7-foot peak storm surge are shown in Figure 31.

TABLE 1

ESTIMATES OF DUNE EROSION POTENTIAL FOR U.S. ARMY CORPS OF ENGINEERS' RECOMMENDED BEACH FILL DESIGN[1]

Peak Surge Level (ft)	Storm Duration (hrs)	Erosion of +14-Foot NGVD Dune Crest (ft)
6.3	24	0
	48	0
	96	4
8.7	24	5
	48	27
	96	57
10.3	24	35
	48	52
	96	93

[1] Numerical estimates do not include the storm dune proposed by the U.S. Army Corps of Engineers at +16 feet NGVD with a 25-foot crest width.

FIGURE 30

INITIAL AND EQUILIBRIUM CONFIGURATIONS FOR BEACH FILL PLAN RECOMMENDED BY U.S. ARMY CORPS OF ENGINEERS (1980)

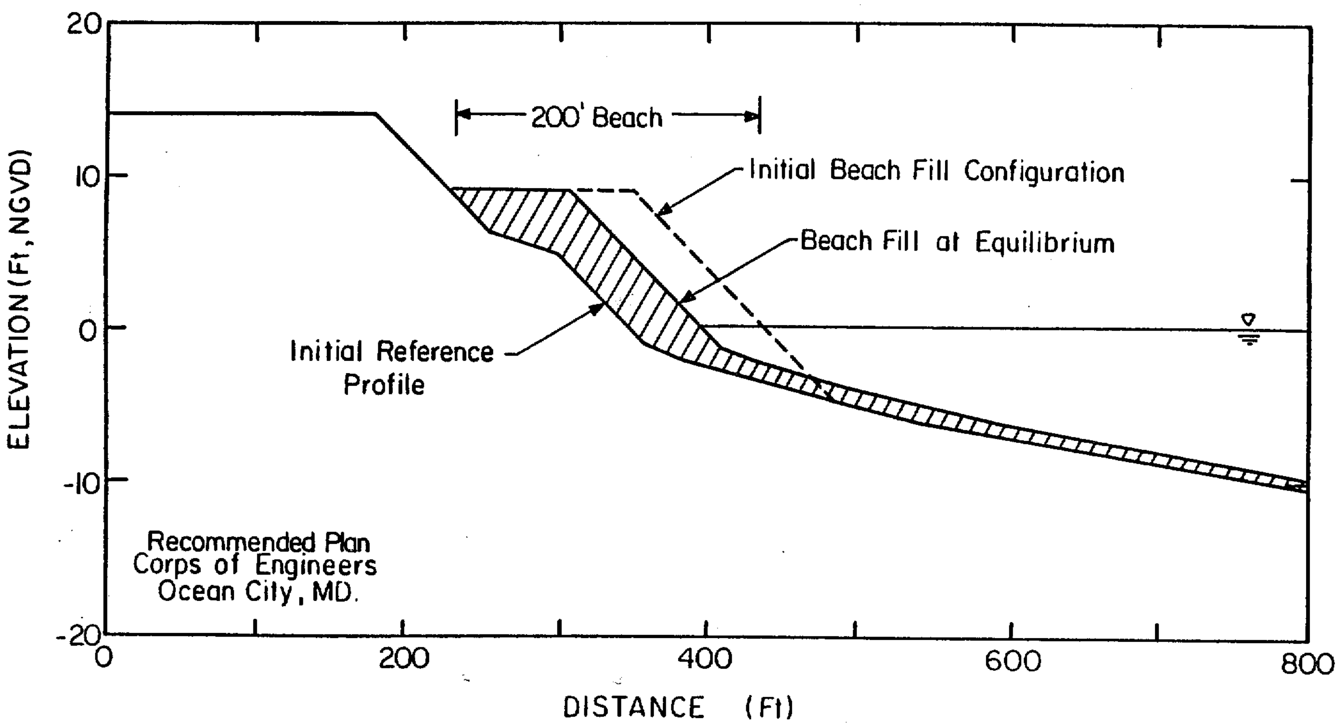
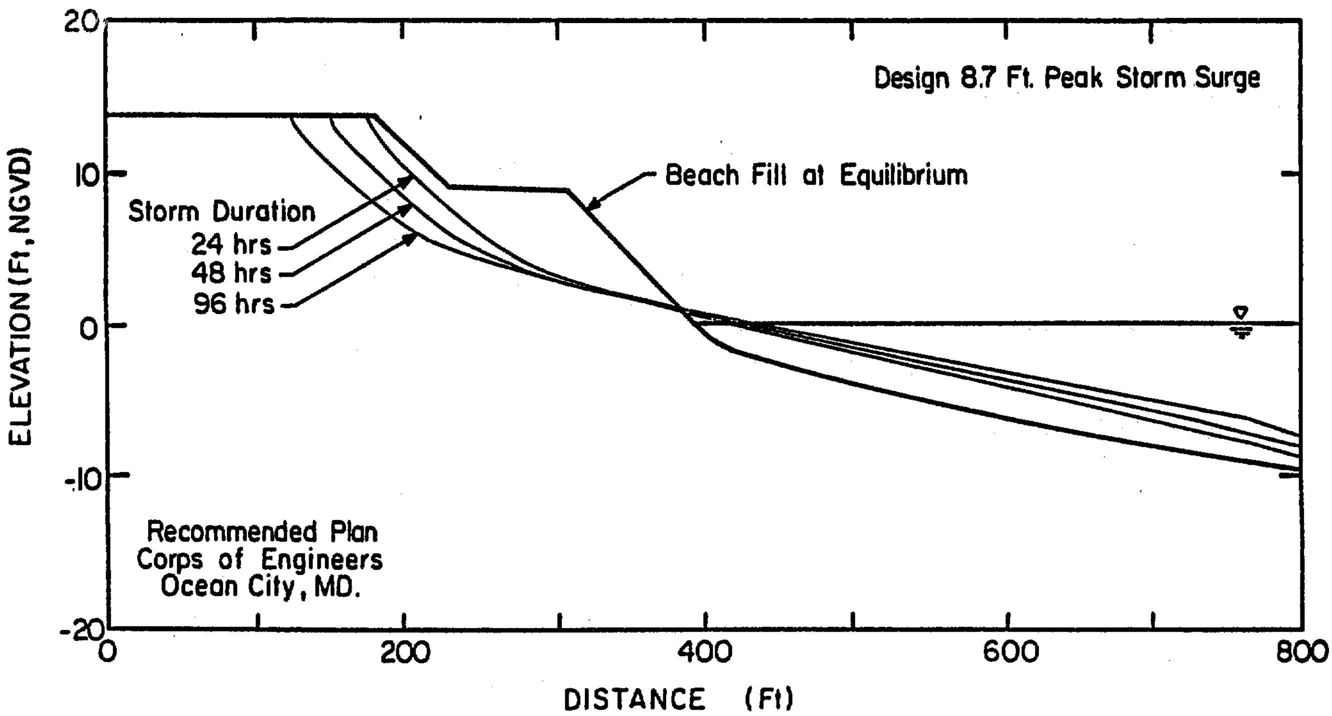


FIGURE 31

ESTIMATED POST-STORM EROSION PROFILES FOR RECOMMENDED BEACH FILL PLAN



SECTION V

APPLICATION TO OCEAN CITY, MARYLAND -- EROSION DUE TO SEA LEVEL RISE

Background

Estimates of the erosion potential due to long-term change in mean sea level are obtained by adjusting the numerical model to determine beach profile response to a new equilibrium given a steady water level that is raised relative to the original still water level. The basic computational procedure determines profile changes in a manner comparable to that suggested by Bruun (1962). The initial profile is characterized by a monotonic $Ax^{2/3}$ form out to an effective depth of closure. In this study, two initial profile forms are established; one with $A = 0.175\ ft^{1/3}$ representing the more mildly sloping Ocean City beach profiles and the other with $A = 0.200\ ft^{1/3}$ representing the majority of the 1965 and 1978 profiles. Depth of closure is assumed to be 28 feet. The berm and dune are established according to the reference profile with an initial dune height of 14 feet.

Numerical computations proceed by raising the water level 1-foot and allowing the profile to achieve a new equilibrium relative to the increased water level; this procedure is then repeated for successive 1-foot water level changes up to a 6-foot increase over the initial level. Final results include the net volume of sand displaced between the initial and final equilibrium profile forms, as well as the estimated dune crest recession and the change in location of the shoreline, defined as the elevation contour which intersects the still water line at any time. In order to maximize the usefulness of erosion calculations for comparison to similar work performed by Leatherman and Everts, results are first presented for basic cases of offshore sediment transport only. These estimates are then modified by accounting for other transport processes to obtain more realistic estimates of potential shoreline adjustment.

Based on Bruun's method, long-term, spatially averaged profile adjustment due to sea level rise occurs in two spatial dimensions as profile adjustment occurs horizontally and vertically. As the nearshore portion of the profile erodes and shifts landward, deposition is assumed to occur both off shore and landward such that the original profile form is always maintained relative to the rising water level. A major assumption is that landward transport of sediment by overwash and/or aeolian processes occurs in sufficient quantities to cause the dune and berm to grow vertically as the profile retreats. For barrier island systems, this implies that the barrier island width and form are also maintained as the entire island cross-section slowly shifts both landward and vertically in response to the slowly rising sea level.

While the theory of barrier island migration may be applicable for many natural areas, there is also evidence of barrier islands "drowning" in place rather than migrating in response to sea level rise. For highly urbanized barrier islands, it is likely that the island will not grow vertically, as it is doubtful that the elevation of the barrier island will be permitted to increase substantially given the existence of roads and residential or commercial structures. In effect, any sand deposited inland of the dune lines by overwash or aeolian transport will probably be returned to the beach face or dune to help prevent further erosion as occurred in Ocean City after the March 1962 storm. Given this scenario, erosion due to sea level rise will occur at a slower pace; however, long-term net erosion would cause the barrier island to narrow and, in effect, drown in place as the sea level continued to rise.

For Ocean City, the drown-in-place scenario seems likely for increases in sea level rise that are expected over the next several decades. In this study, numerical estimates are obtained for a "drowned" profile scenario where the stepwise numerical procedure is applied to the reference profile with an initial dune crest elevation of 14 feet. It is assumed that this elevation will not change appreciably as sea level rise occurs, therefore, the relative dune height continually decreases. For example, after a 3-foot water level rise, the effective dune height is 11 feet. The berm elevation and width are adjusted and maintained at 5 feet above the still water level and 40 feet from the dune toe. Based on these assumptions, the profile form after a 2-foot water level rise corresponds to an existing profile with a 12-foot dune crest; the profile form after a 4-foot water level is identical in form to an existing profile with a 10-foot dune crest, and so on. Therefore, the storm erosion potential of eroded profiles are identical to those already developed for various dune height scenarios. As expected, the magnitudes of dune erosion increase for future conditions.

Sea Level Rise Erosion Estimates

Based on the "drowned" profile scenario, erosion estimates due to sea level rises of 1 to 6 feet are presented in Figure 32. Results are presented for three offshore profile scenarios, based on the two equilibrium $Ax^{2/3}$ profile forms, as described below.

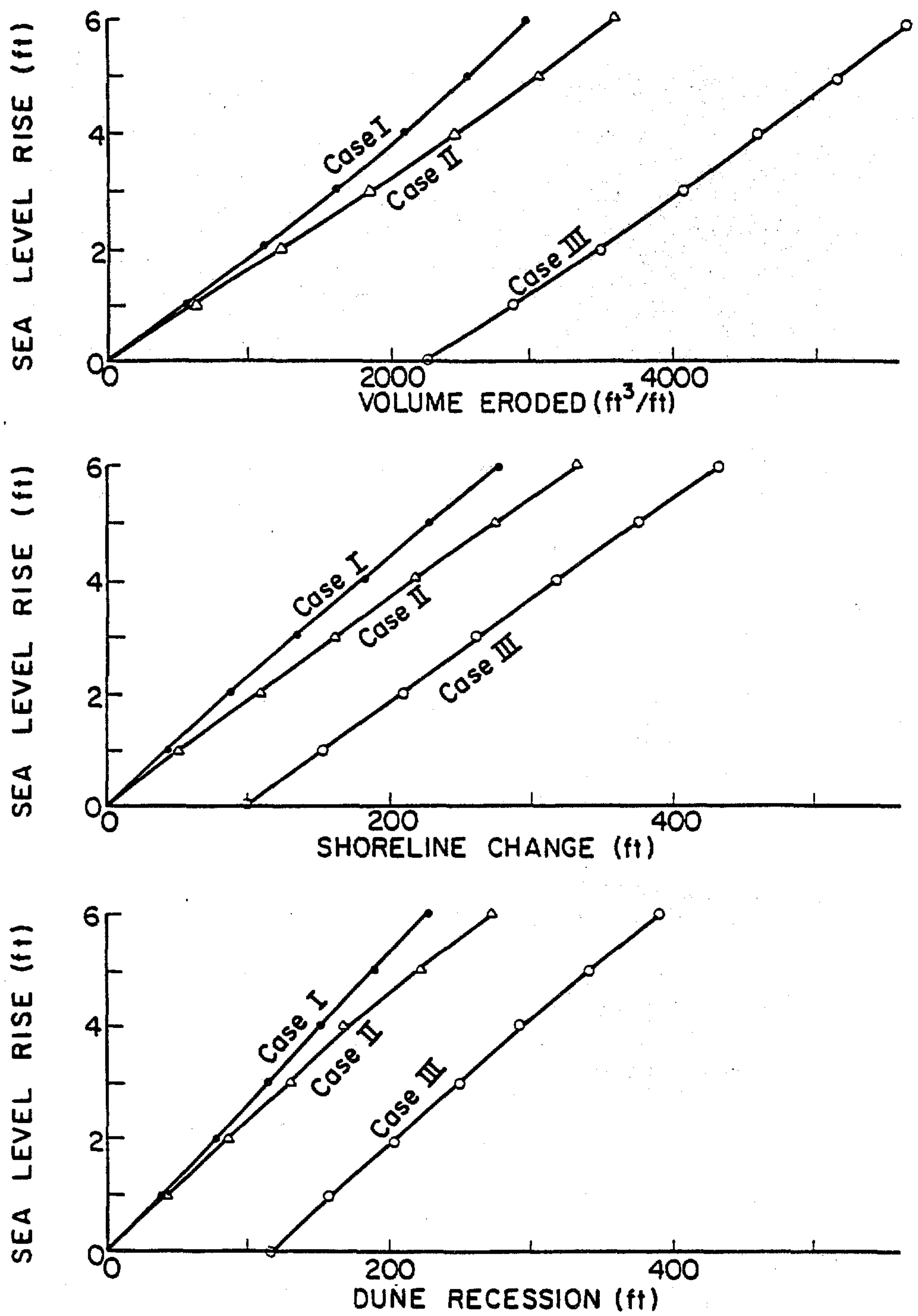
Case I - The existing profile is in equilibrium, characterized by the steeper slope with $A = 0.200\ ft^{1/3}$. The profile after sea level rise also assumes an equilibrium form with $A = 0.300\ ft^{1/3}$.

Case II - The existing profile is in equilibrium, characterized by the milder slope with $A = 0.175\ ft^{1/3}$. The profile after sea level rise also assumes an equilibrium form with $A = 0.175\ ft^{1/3}$.

Case III - The existing profile is not in equilibrium but is characterized by a steeper slope represented by $A = 0.200\ ft^{1/3}$. The profile form readjusts to its equilibrium form characterized by $A = 0.175\ ft^{1/3}$ which is then maintained during sea level rise. This scenario is included to demonstrate the potential impact of a profile shift from an assumed artificially steepened state to a more natural mild equilibrium slope.

FIGURE 32

RESPONSE CHARACTERISTICS OF REFERENCE PROFILE
TO RELATIVE WATER LEVEL RISE



Other assumptions used to generate Figure 32 include: 1) profile adjustment is due to offshore sediment transport only, 2) eroded volumes are assumed to be composed of all sand-sized material, 3) erosion is assumed to respond to the mean rate of sea level rise averaged over a long time period, and 4) the effect of shore stabilization structures is neglected.

The results in Figure 32 also indicate that, as might be expected, the cases with $A = 0.175\ ft^{1/3}$ have a greater erosion potential than the case with $A = 0.200\ ft^{1/3}$; erosion estimates for $A = 0.200\ ft^{1/3}$ are about 83 percent of the erosion estimates for $A = 0.175\ ft^{1/3}$. The differences between the two estimates is probably less than the errors involved in the calculations and the absolute differences are so small, in terms of implications to Ocean City, that either estimate may be considered equally valid. Erosion curves for Case III are determined by first allowing the initial steepened profile, with $A = 0.200\ ft^{1/3}$, to evolve into an equilibrium form, with $A = 0.175\ ft^{1/3}$ at the initial time. This produces a linear offset between curves for Case II and Case III corresponding to the sand deficit that may exist off shore due to recent profile steepening. If this scenario is valid, an erosion potential of 2300 ft^3/ft, corresponding to a potential shoreline recession of 99 feet exists over much of the Ocean City coastline. The mechanisms for this quantum change in profile form and position may occur over short time periods during severe storms and/or may occur over longer periods in response to the steep slope reaching instability limits. Again, this case is included as a hypothetical scenario; the equilibrium characteristics of Ocean City beaches are not known with certainty. In the rest of this report, only Case II is considered in detail.

Corrections to Account for Other Sand Volume Losses

As noted, erosion estimates in Figure 32 are subject to a number of simplifying assumptions. In order to obtain more realistic estimates of erosion magnitudes, several corrections should be applied to the estimates presented. First, since it is known that mud, silt, and clay deposits exist underneath the active sand layers at Ocean City, results should be modified to account for the percentage, p, of material eroded which is sand sized and the percentage, 1-p, which is expected to be removed from the active region after erosion. During storm erosion, these ancient marsh deposits are sometimes exposed on the shoreface; but no corrections are used in storm erosion estimates. During large-scale profile changes to sea level rise, the large volumes of material eroded from the shoreface will normally include greater percentages of non-sand-sized sediment.

Given the percentage of material that is sand of a size compatible with natural sand, the erosion estimates, V_e, in Figure 32 may be modified such that the total volume of material eroded from the beach face is

$$V_t = \frac{V_e}{p}$$

and the total recession of the shoreline or dune may be found to be that originally predicted, R_e, plus an additional amount due to the loss of fine sediment:

$$R_t = R_e + \left(\frac{1}{D+h_o}\right)\left(\frac{1-p}{p} V_e\right)$$

where D is the dune crest height and h_o is the depth of closure, in this case assumed to be 28 feet. Note that as the sea level rise increases, D decreases such that the additional shoreline recession will increase more quickly as sea level rise continues.

Perhaps the most critical corrections that may be made to the erosion estimates in Figure 32 are the inclusion of net sand volume gains or losses over time. Since this analysis is performed along a beach profile of unit width, corrections to the erosion estimates are easily made if net sand volume losses are expressed on a volume per linear foot basis. If the net gains or losses of sediment per linear foot are known to be V_ℓ over some time period, then the total volume of sand eroded from the beach profile due to sea level rise and the net gains or losses is found to be

$$V_t = \frac{V_e}{p} + \frac{V_\ell}{p_2}$$

where the net gains or losses may be adjusted for the percentage of sand sized material, p_2. If net sand gains are experienced, then $p_2 = 1.0$; if net sand losses are experienced then p_2 may equal p, which is a weighted percentage over the profile. Net gains or losses to the profile are reflected as a linear accretion or erosion of the profile over total depth, $D+h_o$, such that the total expected shoreline recession is:

$$R_t = R_e + \frac{1}{D+h_o}\left(\frac{1-p}{p}\right) V_e + \frac{1}{D+H_o}\frac{1}{p_2} V_\ell$$

In this discussion, net gains or losses may be attributed to natural and man-induced causes, including longshore transport gradients, beach nourishment, overwash, aeolian transport, or offshore losses in deeper water.

Estimate of Historical Shoreline Retreat

Based on data presented by Everts (1984), historical shoreline retreat for the period 1930-1980 may be estimated. In order that the methods may be compared directly, input data obtained by Everts (1984) are used to adjust the predicted erosion estimates in Figure 32. According to Everts, the relative sea level rise between 1930 and 1980 was 0.59 feet. From Figure 32, using Case II, this corresponds to a predicted erosion of 370 ft^3/ft and an estimated shoreline change of 31 feet, based only on the profile adjustment to sea level rise. Based on Everts assumed percentage of sand in the profile, $p = 0.75$, an additional volume of 125 ft^3/ft is expected, corresponding to an additional shoreline retreat of 3 feet. Finally, Everts estimates net losses to the 102,300-ft region between Ocean City Inlet and Indian River Inlet, Delaware, to be 1.388×10^7 yd^3 over 50 years for an average loss per linear foot of 3660 ft^3/ft. Adjusting this value for the percentage of sand in the profile, the average eroded volume due to all other losses is 4880 ft^3/ft corresponding to an average shoreline retreat of 116 feet based on the 42-foot total active profile (14-foot dune crest to 28-foot closure depth). Finally, the total estimated eroded volume is 370 + 125 + 4880 = 5375 ft^3/ft with an average shoreline retreat of 31 + 3 + 116 = 150 feet.

The observed average shoreline retreat ranges from about 98 to 115 feet based on low- and high-range average retreat rates 1.9 ft/yr and 2.3 ft/yr from Leatherman (1984a) and the U.S. Army Corps of Engineers (1980). However, since 1961/1962 the shoreline retreat has slowed, seemingly due to groin construction. By extrapolating the 1930-1961 erosion trends of 3.4 ft/yr to 1980 as suggested by Everts, the shoreline would have retreated 170 feet over the 50-year period if the shoreline had responded freely. Based on Everts' method of predicting shoreline retreat due to sea level rise and other volume losses, a calculated shoreline retreat of 184 ft is obtained. A summary of shoreline retreat rates, both observed and predicted is given in Table 2.

Table 2. Summary of Historical Shoreline Retreat Estimates

	Avg. Retreat Rate 1929 - 1980	Avg. Retreat Rate 1929 - 1961	Total Retreat Over 50 Years
Leatherman (1984a)	1.9 ft/yr	-	98
Corps of Engineers (1980)	2.3 ft/yr	-	115
NOS maps, Everts (1984)	-	3.4 ft/yr	170
Everts estimated (1984)			184
Kriebel/Dean estimated			150

The differences between Everts' estimated 184-ft retreat and the 150-ft retreat found in this study appear to be due to calculation procedures and assumed profile forms. The most noticeable difference between the two methods is that the Kriebel/Dean method does not consider sand deposition landward of the dune crest while Everts apparently considers deposition of sand in this region, thus requiring a larger volume of sand to be eroded from the shoreface.

The predicted values of shoreline recession also account for an estimated 1.4×10^6 yd^3 of sand added to the profile in various beach nourishment projects. Since the 3.4 ft/yr observed erosion rate does not include the effects of this net addition of sand, numerical estimates should also be made without this sand volume. After accounting for this sand volume added by beach nourishment, the total net loss of sand lost from the profile is 5210 ft^3/ft over a 50-year period. This corresponds to a 124-ft shoreline recession which, when added to the 34-ft recession due to sea level rise, gives a total estimated shoreline recession of 158 feet, somewhat closer to the 170-ft extrapolated value.

Calculation of Future Erosion Rates

Estimates of future erosion trends are obtained by combining the results of profile adjustment to increased water levels for Case II with the projected net sand volume losses to the profile. This analysis is carried out for three sea level rise scenarios, as indicated in Table 3, corresponding to a continuation of the existing trend and two more severe scenarios developed by the EPA and modified by Everts to account for subsidence. In order to compare the results of this study with those of Everts, the net sand volume losses identified by Everts are also adopted. These include a net loss of 270,000 yd^3 per year due to longshore transport out of Fenwick Island and losses of about 30,000 yd^3 to offshore areas. After adjusting for the loss of non-sand-sized material, net sand volume losses from the profile are taken to be 106 ft^3/ft per year. This loss rate is applied uniformly over the 95-year period from 1980 to 2075. As Everts discusses, however, there are several estimates of net losses available, and future net losses may vary considerably from present estimates.

Table 3. Relative Sea Level Rise Scenarios Cumulative Change in Mean Sea Level Elevation

Period	Current Trend	Mid-Low Estimate	Mid-High Estimate
1980 - 2000	0.24 ft	0.40 ft	0.55 ft
2000 - 2025	0.53 ft	1.13 ft	1.55 ft
2025 - 2050	0.83 ft	2.14 ft	3.00 ft
2050 - 2075	1.13 ft	3.55 ft	5.05 ft

Figures 33 and 34 indicate the projected future erosion trends based on the three sea level rise scenarios and the estimated net sand volume losses. The most striking result of the analysis is the large erosion potential that exists due to the projected net sand volume losses. Over the 95-year period, a total loss of 10,070 ft^3/ft is estimated for a total loss of 17,600,000 yd^3 over the Ocean City shoreline (based on a 46,650-ft total length from Ocean City Inlet to the Maryland-Delaware state line). In Figure 34, these net volume losses are assumed to be applied uniformly over the profile cross-section from the dune crest out to the depth of closure and, while causing a net retreat of the profile, do not change the shape or vertical position. A profile retreat of 2.6 ft/yr or 246 feet over the 95-year period is projected due to net sand losses from the profile.

In contrast to the net sand volume losses, the volume of material eroded due to sea level rise is not lost from the profile but is simply redistributed from the beach face to off shore. Numerical estimates indicate that erosion will occur between the dune crest and a nodal depth of about -7 feet, with deposition occurring from -7 feet to the depth of closure. From Figures 33 and 34, it is evident that this redistribution of sand erodes a volume of sand from the beach face that is small compared to the net sand volume lost due to longshore or offshore transport. However, because this volume is removed from the beach face and not over the full depth of profile, the shoreline retreat

FIGURE 33

FUTURE EROSION ESTIMATES DUE TO SEA LEVEL RISE AND NET SAND VOLUME LOSSES

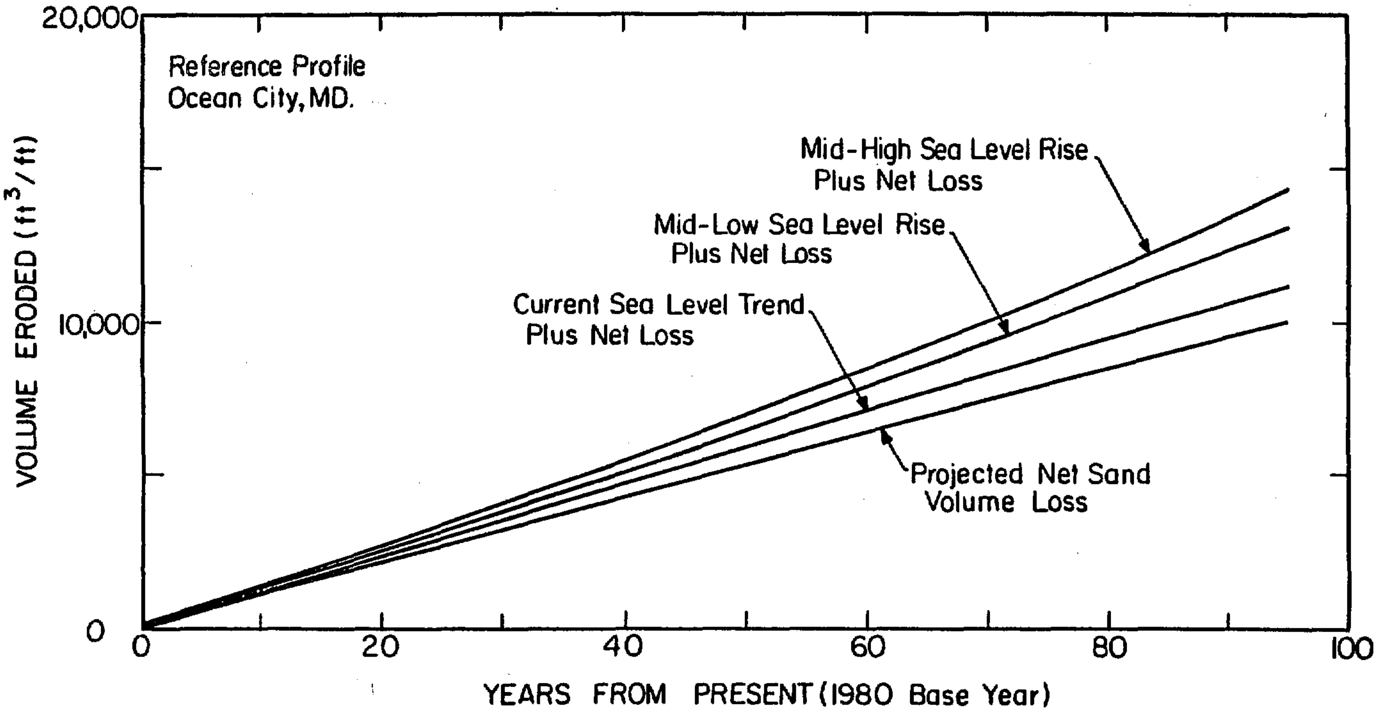
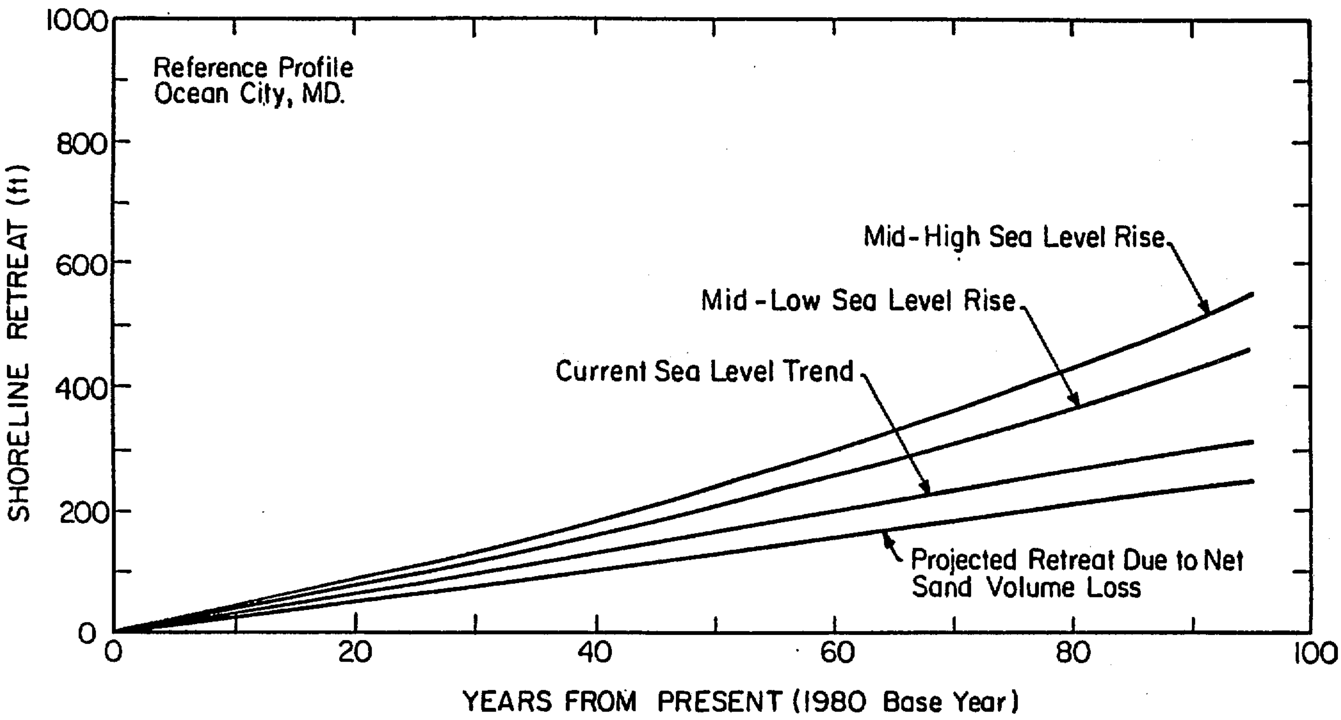


FIGURE 34

FUTURE SHORELINE RETREAT ESTIMATES
DUE TO SEA LEVEL RISE AND NET SAND VOLUME LOSSES



due to sea level rise may be comparable to that caused by net sand volume losses.

A continuation of the existing sea level rise trend is expected to produce an average erosion of about 10 ft^3/ft per yr and a shoreline recession of about 0.7 ft/yr. The combined effects of this sea level rise trend with net sand volume losses are an average shoreline recession of about 3.3 ft/yr, comparable to the 3.4 ft/yr observed from 1929 to 1961. The existing rate of sea level rise therefore accounts for about 20 percent of the historical shoreline retreat rate and about 10 percent of the volume of material eroded.

Under the scenarios of accelerated sea level rise, erosion response, and particularly shoreline response, is increased substantially. Based on the mid-low range scenario an eroded volume of 2940 ft^3/ft and a shoreline recession of 210 feet are projected in addition to erosion expected due to net sand volume losses over 95 years. When combined, the net sand volume losses and the erosion due to the mid-low sea level rise produce a total potential shoreline recession of about 460 ft, corresponding to a 4.8 ft/yr average.

The mid-high range sea level rise scenario yields a sizeable 4075 ft^3/ft additional eroded volume nearshore with a 305-ft potential shoreline recession. When combined with net sand volume losses, a total shoreline recession of 550 ft is expected after 95 years for an average of nearly 5.8 ft/yr. Due to the non-linear erosion response to the accelerated sea level rise scenarios, projected erosion rates also accelerate over the 95-year period. Over the first 20 to 50 years, erosion rates are closer to the existing trend. For example, over the first 50 years erosion rates of 4.0 ft/yr and 4.8 ft/yr are projected for the mid-low and mid-high scenarios respectively. In later years, erosion rates increase rapidly as sea level rise accelerates and as the assumed active profile depth decreases due to the "drowned" profile assumption.

As noted, numerical model does not account for the actual barrier island cross-section landward of the dune crest and, instead, this area is approximated by a uniform elevation. It is recognized that this is not a realistic condition since average island elevations decrease to +8 feet and +4 feet at distances of 200 and 400 feet landward of the dune crest, respectively. Because of this natural decrease in elevations toward the bayside of the barrier island, actual shoreline retreat should be increased over values shown in Figure 34 since a progressively smaller sand reservoir is available in reality. However, the errors involved are on the order of only 5 to 10 percent for a shoreline retreat of up to 200 feet. Predictions in Figure 34 are therefore assumed to be reasonable for periods of up to 40 years for the mid-high case, 50 years for the mid-low case, and over 60 years for the extension of the current trend. Beyond these time periods, conditions are so uncertain in terms of human response, such as possible beach nourishment, dike construction, or seawall construction, that errors in predictions of shoreline retreat are of little concern.

In summary, the impacts of projected sea level rise scenarios are significant, with the mid-high scenario resulting in a near doubling of the existing (i.e., pre-1961) erosion rate. Sea level rise erosion is most easily interpreted in terms of the erosion potential due to net sand volume losses. As noted, the existing sea level rise trend has contributed to only 20 percent of the observed shoreline retreat between 1929 and 1961. For the mid-low and mid-high sea level rise scenarios, sea level rise accounts for 44 to 55 percent of the total projected shoreline response to the year 2075.

Mitigation Requirements - Long-term Erosion Trends

Mitigation requirements for sea level rise and net sand volume losses are estimated based on the premise that the existing shoreline position is to be maintained. Net sand volumes that must be added to the profile to restore the shoreline position are estimated according to the predicted shoreline retreat times the active profile depth of about 42 feet. This total volume is larger than the estimated eroded volume since the equilibrium profile form must be maintained at all depths, and this cannot be accomplished by simply returning the eroded volume back to the profile. The shoreline position could temporarily be re-established by adding the eroded volume back to the nearshore portion of the profile, but since this would result in a steepened profile, it would tend to be unstable in the long-term.

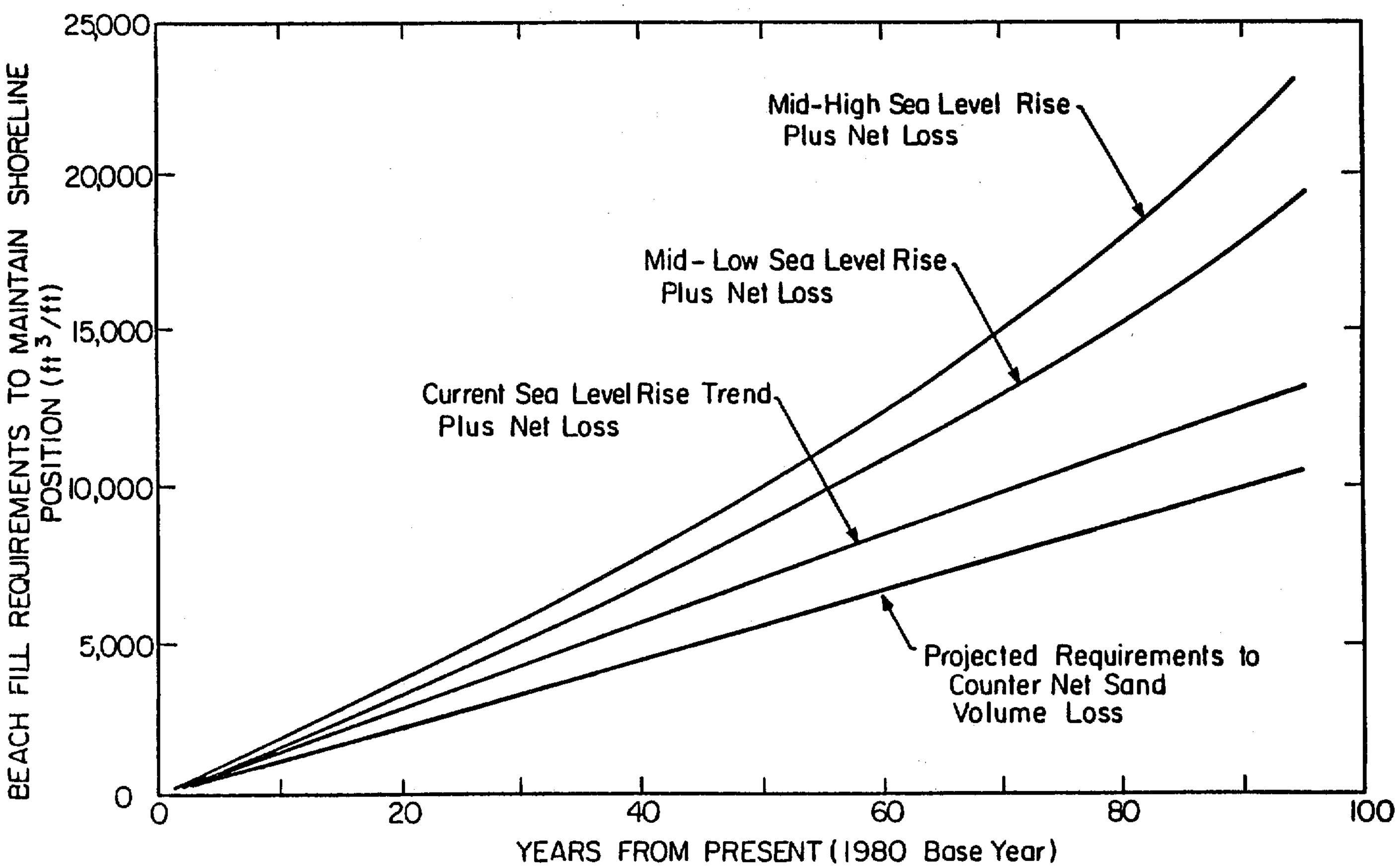
In Figure 35, estimated beach nourishment requirements are given for the range of scenarios considered to the year 2075. The estimated volumes are quite large and range from a minimum addition of 106 ft^3/ft per yr to replace sand lost due to longshore or offshore transport, to a maximum addition of 245 ft^3/ft per yr for the mid-high range sea level rise scenario. Total sand volumes that must be added over the 46,650-ft Ocean City shoreline range from an average of 185,000 yd^3/yr to 425,000 yd^3/yr for total volumes of 17,600,000 yd^3 to about 40,000,000 yd^3 by the year 2075. These volumes are for fill material that has a grain size distribution compatible to the existing natural grain size distribution; larger volumes are required if a fraction of the fill material is too fine to remain stable under the existing wave climate.

Based on the estimated mitigation requirements, significant quantities of sand must be added to the area from outside of the active region considered, bounded by Ocean City Inlet, the Maryland-Delaware state line, and the closure depth of 28 feet. While a portion of the 17,600,000 yd^3 lost from the system may be recycled by dredging from bounding inlets and returning to source areas or retained through additional holding structures such as groin fields, the impact of this remedial action on adjacent beaches outside the system should be considered. Similarly, the dredging of material from offshore sand sources should take place outside of the active profile so that it does not contribute to a sand deficit in offshore regions. In this case, dredging should not take place landward of the depth of closure.

Finally, it should be emphasized that natural processes may aid in returning sand back into the system. As the profile retreats landward, offshore slopes become milder and a broad shelf is created near the closure depth. As this occurs, a net onshore transport of sand may occur in this region. This would tend to offset the net sand volume now lost to offshore areas. This response mechanism is not included in simulations but may slow profile retreat.

FIGURE 35

FUTURE MITIGATION REQUIREMENTS
TO PREVENT SHORELINE RETREAT



Relative Effects of Long-term and Short-term Erosion Scenarios

The combined effects of long-term profile adjustment, which is attributable to sea level rise and net sand volume losses, and short-term, storm-induced erosion are summarized in Figures 36 through 38. In these examples, the range of erosion characteristics for all storm surge elevation and duration scenarios is superimposed on the estimated long-term eroded volume and dune recession for each sea level rise scenario. For this comparison, dune recession is used instead of shoreline recession since, during storms, the shoreline position may advance seaward as the beach face is flattened and as the dune recedes. As noted earlier, storm erosion estimates range from 500 to 1400 ft^3/ft with dune recession of 0 to 136 ft for the existing reference profile with a 14-ft dune crest. As sea level rise advances on the dune crest, the relative dune height decreases under the drowned profile scenario, therefore the potential for dune retreat increases over time.

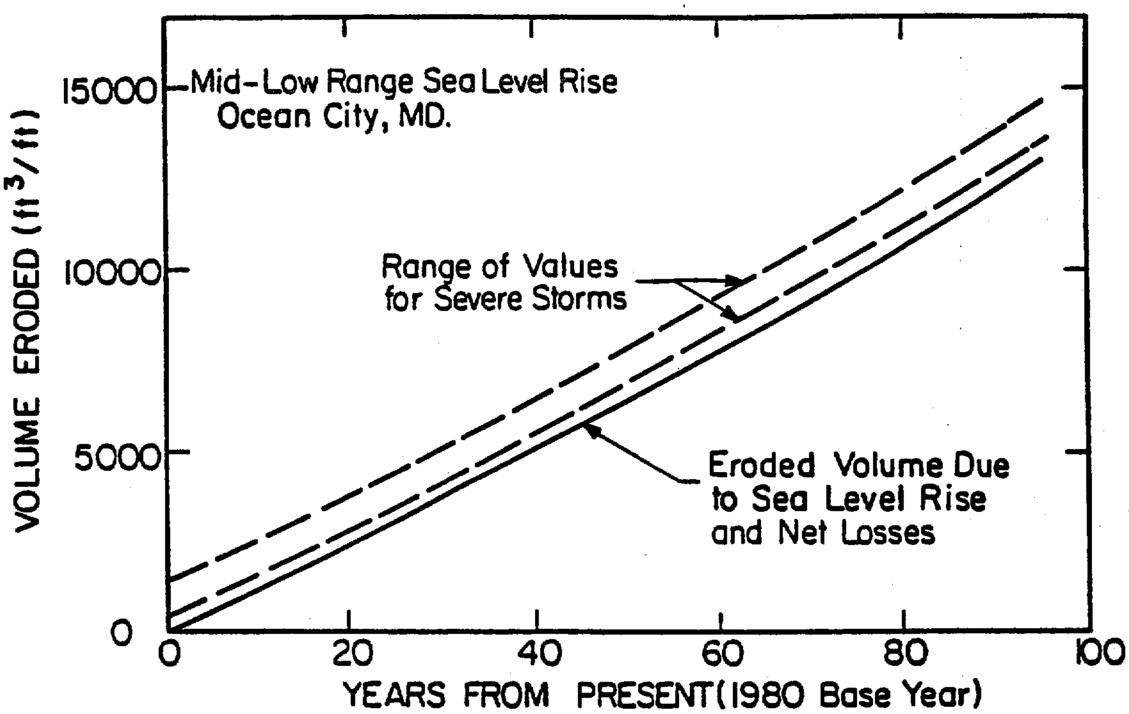
For interpretation of erosion effects, Figures 36 through 38 indicate that the erosion potential of even the worst storm scenario is small relative to long-term erosion expected over the 95-year period. In terms of eroded volume, the storm erosion potential that exists today is roughly equivalent to about 10 years of the more progressive erosion expected due to sea level rise and net sand volume losses. In terms of dune recession, a severe storm may cause the equivalent of 30 to 50 years of long-term erosion. It should be emphasized, however, that while a portion (perhaps all) of the material eroded during a storm may be returned to the beach face by natural recovery processes, most sand lost due to longshore transport gradients or sea level rise is permanently removed from the beach face.

For erosion mitigation, these results suggest that appropriate planning must address two erosion scenarios on two far different time scales. Short-term erosion mitigation requirements should concentrate on the potential impact of severe storms where sudden, dramatic erosion may occur at any time. By today's standards, mitigation requirements to provide protection against severe storms represent substantial but not prohibitively large sand volumes. As an example, mitigation requirements for the storm scenarios tested range from a net addition of about 1000 ft^3/ft to about 2100 ft^3/ft for the reference profile based on Figure 29. Since this is the net addition above the still water level after the fill has achieved equilibrium, an initial overfill of about 700 to 900 ft^3/ft is required to provide sand necessary to achieve equilibrium over the normal active profile. As a conservative estimate, a total addition of 2000 ft^3/ft to 3000 ft^3/ft is required to provide storm protection. Over the 46,650-ft Ocean City shoreline, an addition of 3,500,000 to 5,000,000 yd^3 is then required.

When these short-term requirements are compared to long-term mitigation requirements of 17,600,000 to 40,000,000 yd^3, however, the importance of long-term planning is evident. It has been found that mitigation requirements estimated on the premise that the current level of storm protection is to be maintained, are nearly identical to those required to maintain the existing shoreline position. Although maintenance of the existing dune crest position does not require as large a volume as maintenance of the existing shoreline

FIGURE 36

FUTURE EROSION LIMITS DUE TO STORMS AND LONG-TERM EROSION FOR EXTENSION OF CURRENT SEA LEVEL RISE TREND



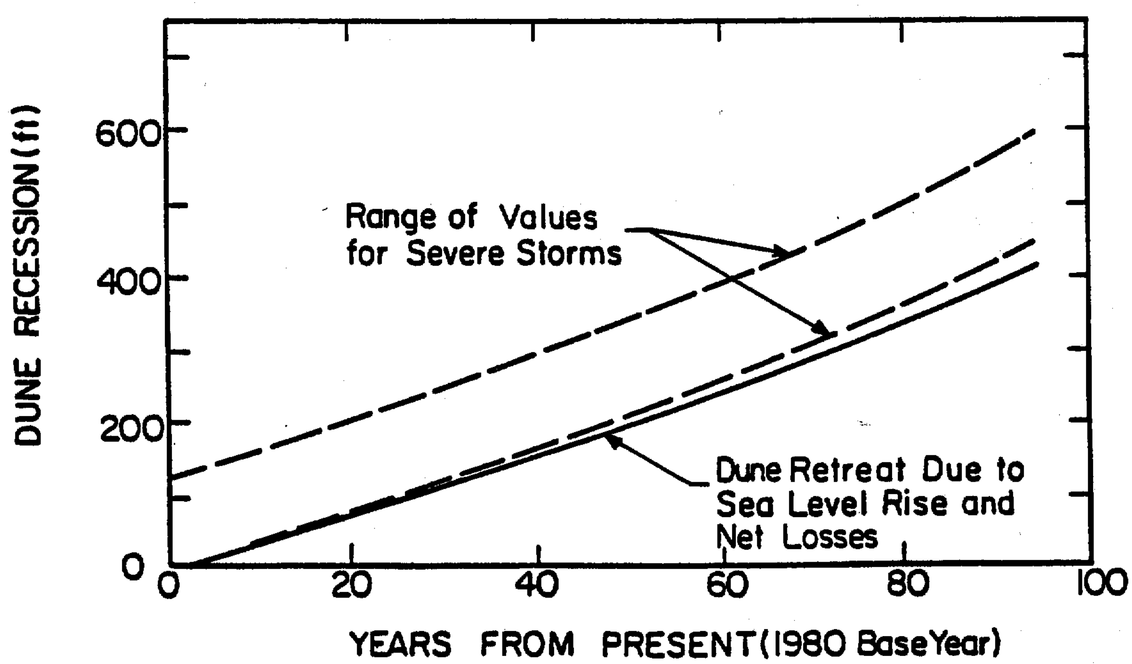
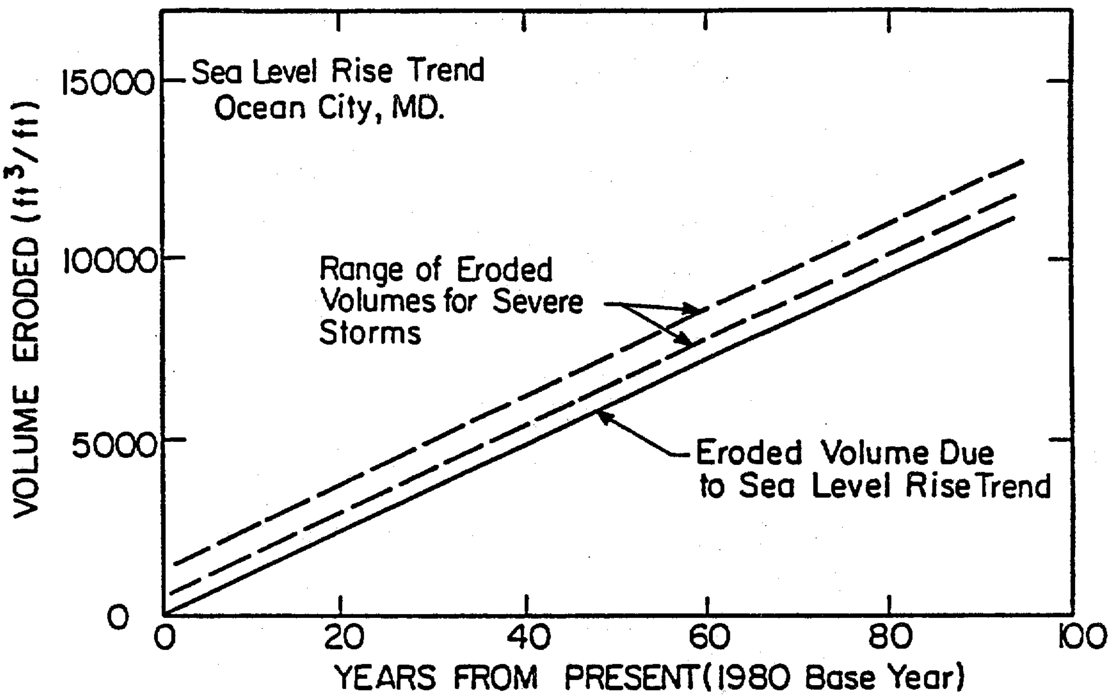


FIGURE 37

FUTURE EROSION LIMITS DUE TO STORMS AND LONG-TERM EROSION FOR MID-LOW SEA LEVEL RISE SCENARIO



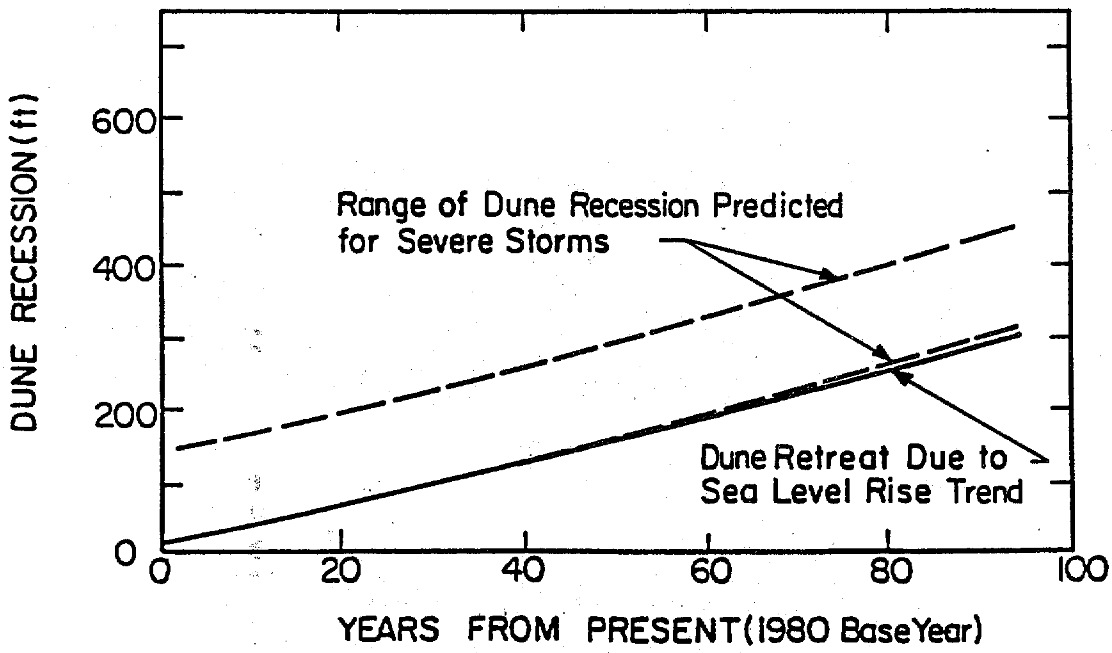
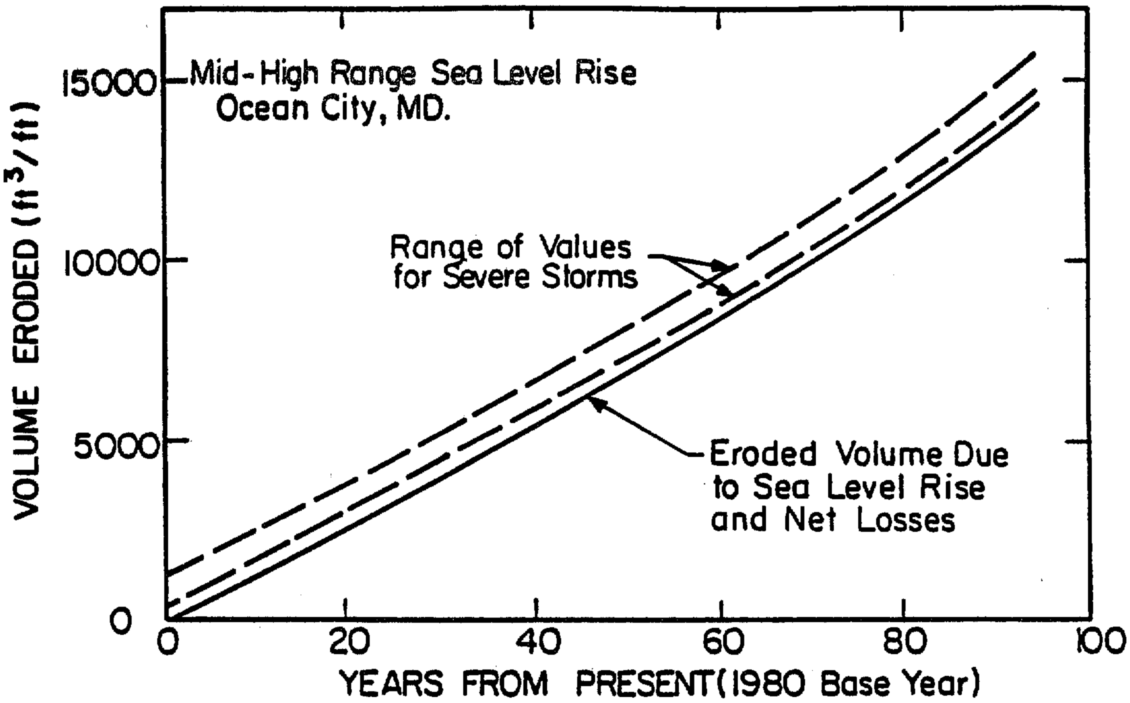
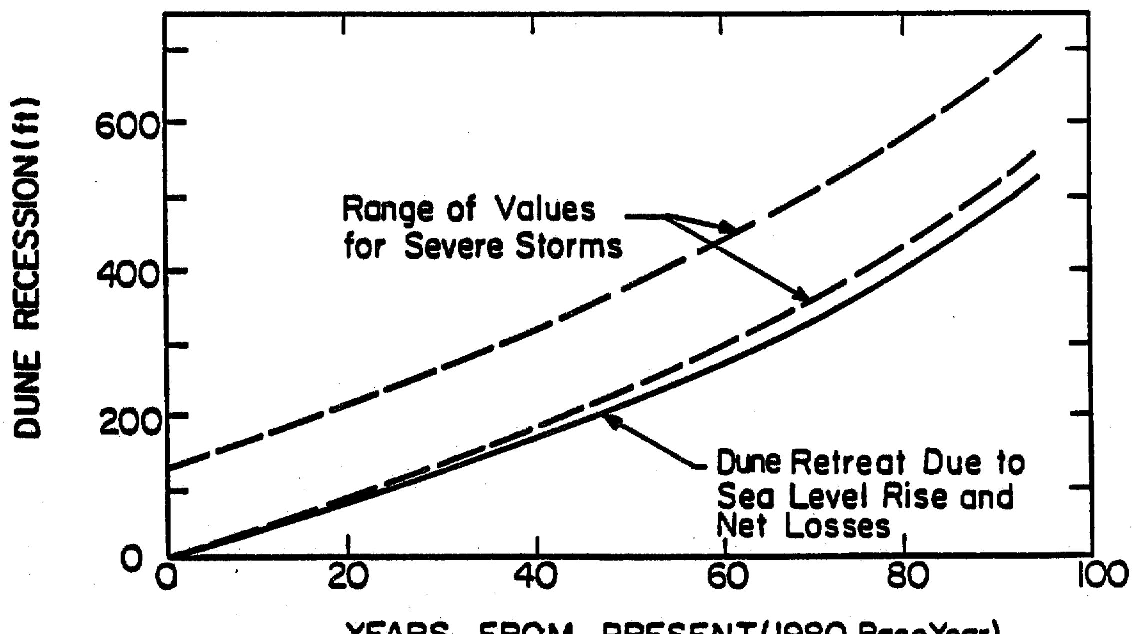


FIGURE 38

FUGURE EROSION LIMITS DUE TO STORMS AND LONG-TERM EROSION FOR MID-HIGH SEA LEVEL RISE SCENARIO





position, it has been found that an additional sand volume is required to raise the "drowned" dune crest back to the 14-ft elevation at the existing location. These two effects tend to offset each other yielding, for practical purposes, identical mitigation volume requirements even though fill configurations are slightly different. Based on the general mitigation requirements in Figure 35, it is evident that beach fill volumes required to provide complete short-term storm protection today are small in comparison to beach fill volumes required to maintain existing levels of protection over 50 or 100 years.

SECTION VI

SUMMARY AND CONCLUSIONS

Based on numerical analyses of the erosion potential due to severe storms and various sea level rise scenarios the following general conclusions are made:

1) The erosion potential of severe storms of 10- to 500-year return periods ranges from 500 to 1400 ft^3/ft eroded above the mean sea level contour with corresponding probable dune retreat of 50 to 100 feet and possible dune retreat of 140 feet. These estimates are for a reference profile with a 14-foot dune crest height; dune retreat distances increase substantially for lower dunes.

2) The estimated erosion potential of the March 1962 storm is 974 to 1129 ft^3/ft with dune recession of 58 to 71 feet for the reference profile. These estimates appear reasonable compared to available qualitative descriptions of storm damage; however, significant dune breaching and overwash occurred during the 1962 storm. These natural occurrences are not simulated in the numerical model.

3) Based on estimates of the erosion potential of typical Ocean City profiles, existing dunes will be quickly eroded or overtopped by most of the severe storms tested. A useful application of the predictions would be a mapping of dune erosion, overtopping, overwash, and storm flooding potential to identify areas in need of dune restoration.

4) Mitigation requirements for storm erosion are developed based on the predicted volume eroded during a storm in the absence of mitigation. In general, safe beach fill designs require a net addition of 1.0 to 1.6 times the predicted eroded volume to be placed above the mean sea level contour. Actual in-place beach fill requirements are larger due to the natural readjustment of artificial fill to the incident wave climate. Storm protection for the 100-year storm surge seems to require initial beach fill volumes of 3,500,000 to 5,000,000 yd^3 of sand over the Ocean City shoreline.

5) The beach fill plan recommended by the U.S. Army Corps of Engineers is found to be adequate for design conditions of the 100-year storm surge with up to 24-hour durations. Although the design is not adequate for more severe storms, the probability of occurrence of more severe conditions is small; for practical design

the Corps' plan seems to be sufficient although periodic renourishment schemes have not been evaluated.

6) The erosion potential due to three sea level rise scenarios and net longshore or offshore sand volume losses result in average shoreline retreat rates of 3.3 to 5.8 ft/yr. These estimates reflect the potential retreat rates without mitigation measures.

7) Based on extrapolation of existing sea level rise trends, predicted shoreline erosion rates of 3.3 ft/yr agree with observed rates of 3.4 ft/yr between 1929 and 1961. Since 1961, groin construction and beach nourishment seem to have slowed the average shoreline retreat rate. However, offshore areas have continued to retreat at historical rates, resulting in what appears to be an artificially steepened profile.

8) Based on two accelerated sea level rise scenarios, the potential shoreline retreat rate is slightly greater than the historical retreat rate over the next 20 to 40 years but accelerates rapidly in later years. While existing erosion rates are dominated by net longshore or offshore sand volume losses, erosion rates under accelerated sea level rise scenarios are almost equally influenced by net volume losses and profile readjustment to sea level rise.

9) Mitigation requirements for maintaining the existing shoreline position are found to be 116 ft^3/ft per yr to 245 ft^3/ft per yr on average with total sand volumes of 19,000,000 yd^3 to over 40,000,000 yd^3 required over the 46,650-ft Ocean City shoreline by the year 2075. Since sea level rise scenarios predict accelerated water level rise over time, mitigation requirements also increase non-linearly over time. Non-linear shoreline response over time also occurs due to the assumed fixed dune crest elevation as sea level rises.

10) The erosion potential of severe storms is found to be equal to approximately 10 to 30 years of long-term erosion due to sea level rise and net volume losses. However, profiles will recover somewhat after storms, whereas long-term erosion is permanent. Mitigation requirements for providing the current level of storm protection are found to be approximately equal to mitigation requirements for maintaining the existing shoreline position. Therefore long-term sand volumes of 19,000,000 to 40,000,000 yd^3 are required to maintain

the current level of storm protection over the 95-year period. An additional 3,500,000 to 5,000,000 yd^3 are required to provide additional storm protection for the 100-year storm surge.

While storm erosion estimates are believed to be accurate to within probable errors of ±25 percent, erosion estimates due to sea level rise are considered less accurate. It must be recognized that the ability to forecast erosion at any location is not precise due to a general lack of long-term data on beach profile response to sea level rise. For an urbanized area like Ocean City, apparent steenpening of offshore profiles and attempts to stabilize the shoreline complicate prediction further. Erosion estimates due to sea level rise and net sand volume losses confirm that current erosion problems will accelerate under accelerated sea level rise conditions. However, the absolute values of the actual shoreline retreat should be considered highly variable; estimates given in this report represent a best estimate based on current methodologies and field data.

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